DEPARTMENT OF COMMERCE

BULLETIN
OF THE
BUREAU OF STANDARDS

VOLUME 9

1913

41

INSTRUMENTS AND METHODS USED IN RADIOMETRY—II

By W. W. Coblentz

CONTENTS

	Page
I. Introduction	7
II. The Radiomicrometer	8
III. The Thermopile	12
1. Brief description of thermopiles of recent construction	12
2. Construction of a bismuth-silver thermopile.	
(a) Linear thermopiles	15
(b) Surface thermopiles	22
(c) Thermopile-galvanometer sensitivity testing device	33
IV. The Bolometer with its Auxiliary Galvanometer	34
1. Historical summary	34
2. The construction of sensitive bolometers	37
3. Comparison of sensitiveness of various bolometer-galvanometer combinations	38
4. Construction of a vacuum bolometer	39
5. Electric batteries for bolometers	43
6. Radiation sensitivity of different parts of a bolometer strip	44
V. Selective Radiometers	45
VI. A New Form of Radiometer	47
VII. Summary	48
Note I. The Callendar Radiobalance	51
Appendix I	56
The Auxiliary Galvanometer	56
(a) Sensitiveness of galvanometer	58
(b) Proportionality of galvanometer deflections	59
(c) Magnetic shielding	60

I. INTRODUCTION

In the present paper an attempt is made to give the latest attainments in the construction of instruments used in measuring spectral radiation. In a future paper it is purposed to give an account of an intercomparison of various types of radiometers used in measuring undispersed ("total") radiation, including the determination of the same in absolute measure.

The arrangement of the subject matter follows closely the outline of a previous [1] paper on this subject, to which reference must be made for more complete information on certain topics.

The word "radiometer" will be used instead of the more clumsy expression "radiation meter," in speaking of these instruments in general, and to avoid confusion with the "Nichols radiometer" the latter will be distinguished by the use of the inventor's name.

To the familiar question "What instrument should I use?" the reply may be made that it is not always an easy matter to decide in the beginning of a new investigation which type of instrument will prove the most satisfactory. For work requiring the highest attainable precision with a great deal of routine observation, extending over a long period, the writer has adopted the vacuum bolometer because of its quickness of action and because of the wide range of variation and ease of testing its sensitivity. But the instrument is very elaborate and requires very careful handling. In many researches where the actual time consumed in observation is a matter of only a few weeks a radiomicrometer or thermopile would be sufficiently accurate, and would require less attention. The writer has both a vacuum bolometer and a thermopile in working order, and uses them with the same galvanometer.

II. THE RADIOMICROMETER

Within the past two years the radiomicrometer has come rapidly to the front as a competitor with the other types of radiometers, such as the Nichols radiometer, the thermopile, and the bolometer. The fact that it is not sensitive to magnetic disturbances makes this a very useful instrument deserving a more general adoption.

Féry [2] has recently described a radiomicrometer consisting of a loop of copper joined at the bottom by means of a short wire of constantan. The two junctions were placed at the same height, side by side, and covered with strips of silver 6 by 12 by 0.3 mm. The strips of silver were polished on the rear and blackened with platinum black on the front. For a candle and scale at 1 m the deflection was 23 cm.

---

[1] This Bulletin 4, p. 391; 1908.

[2] Féry: Bull. Seances Soc. Franc. de Phys., p. 148; 1908.

One of the most noteworthy radiomicrometers described recently is the one constructed by Schmidt [3] in the laboratory of Prof. Rubens, and it has since been used by the latter and his collaborators in exploring the region of longest heat waves yet measured. The suspended system of Bi-Sb, as made by Schmidt, is practically the same as was previously described.[4] Instead of a glass rod at the top he used one of aluminum, 50 mm long and 0.5 mm diameter, and a mirror 4 mm diameter. The deflection on a 13 to 14 second period, without the concentrating funnel, was 20 cm, for a stearin candle at 1 m and a scale at 2.5 m, which is equivalent to 8-cm deflection for a candle and scale at 1 m.

Hollnagel [5] found that the instrument was subject to irregular deflections caused by air currents, the adiabatic expansions and compressions causing temperature variations in the thermojunctions. He therefore modified this instrument and placed it in a vacuum.

Using the conical receiver, Rubens and Hollnagel [5] observed a deflection of 10 cm for a candle at 6 m and scale at 3 m, for a single swing of 10 seconds. This is equivalent to 120 cm for a candle and scale at 1 m. Just how much the conical receiver has increased the apparent sensitiveness is unknown. In the original description of the Rubens thermopile,[6] the galvanometer deflection was given as 54 mm with the conical receiver and as only 22 mm without the receiver. A fair estimate of the radiomicrometer deflection, without the conical receiver, is therefore about 50 cm for a candle and scale at 1 m, the complete period being 20 seconds. The area of the exposed surface is not given, but judging from Schmidt's description of a linear junction of Bi-Cu, consisting of a strip of Bi, 18 by 1 by 0.4 mm, joined to a copper wire 0.13 mm diameter, and from the fact that the opening in front of the junction was 5 mm in diameter, the area of the receiving surface was of the order of 18 to 20 $mm.^2$ However, since an ordinary candle gives readings 10 to 15 per cent higher than that of a stand-

---

[3] Schmidt: Inaug. Diss. Berlin; 1909. Ann. d. Phys., **29**, p. 1003; 1909. Also used by Meyer, Ann. d. Phys., **30**, p. 612; 1909.

[4] This Bulletin, **4**, p. 391; 1908.

[5] Hollnagel: Inaug. Diss., Berlin; 1910. Rubens and Hollnagel: Sitzber. Akad. Wiss., **4**, p. 26; 1910, Berlin. Rubens and Wood: Sitzber., **52**, p. 1124; 1910.

[6] Rubens: Zs. f. Instk., **18**, p. 65; 1898.

ard sperm candle, and since the radiation tests were not made in the same manner as herein described, no accurate comparison can be made of these instruments. In the investigations of Rubens and Wood,[7] the sensitiveness of this instrument was increased so that, using the conical receiver, the deflection was increased to 70 cm (scale distance not given but probably 3 m as in previous work) for a candle at 2 m, the instrument being covered with a quartz window 1 mm thick.

In a previous paper,[8] the writer described a vacuum radiomicrometer. From later experience, it seems desirable to try constantan instead of bismuth as then used.

Recently [9] a new form of suspension was made for this radiomicrometer. The suspension consists of two junctions of bismuth and silver, with a copper loop, and it was made linear for spectral radiation work. It was found that by dropping the molten metal from a height [9] of about 1 m it would spatter out into a thin, well-annealed plate, which could then be rolled to 0.02 to 0.04 mm thickness. The dimensions of the present junction are: Bi= 8 by 1 by 0.03 mm, Ag=3 by 1 by 0.01 mm and copper wire=0.08 mm diameter. The central, active parts of the junctions were painted on one side with a mixture of platinum black, lampblack, and a little shellac in alcohol. The window covering the junctions consisted of a film of glass blown so thin that it showed interference colors. Such a film absorbs but little in the spectrum, except at 8 to 9μ.[10]

For a standard sperm candle at 3.1 m and scale at 1 m, with all extraneous light excluded except that which passed through a long, blackened tube, the deflection was 22 cm (for a single swing of 25 seconds) or more than 200 cm at 1 m. For a single swing of 10 seconds the deflection was at least 50 cm. It is therefore apparent that this form of junction is as sensitive as any heretofore described. The weight of the complete suspension was a little less than 10 mg. The sensitiveness of this suspension was not

[7] See footnote 5, p. 9.

[8] This Bulletin, 2, p. 479; 1906.

[9] This Bulletin, 7, p. 243, 1911. Since writing this paper Pfund (Amer. Phys. Soc., meeting Dec. 27, 1911) has described a similar method, which enabled him to produce fine filaments of the order of 0.01 mm diameter. (See Phys. Rev., 34 p. 228; 1912.)

[10] See Investigations of Infra-Red Spectra, Vol. II, p. 65; 1906.

very much greater than that of a similar suspension having but a single thermojunction, which is in accordance with the theory

The purpose in describing this form of instrument is not so much to show its sensitiveness as to indicate directions in which further improvements are possible. On account of the difficulties in preparing a nonmagnetic loop, there is still much room for improvement by combining the Nichols radiometer and the radiomicrometer. For detecting electrical waves the system can be made still lighter and the heating arrangement can be brought close to the junction as in the Duddell [11] ammeter, or by using a Klemenčič thermojunction [12] and radiomicrometer as described by Pierce.[12] The point receiver thermopiles of bismuth and silver, described on a subsequent page, would be more sensitive and quicker acting than obtains in the present commercial instruments (e. g., ammeters).

In table I are shown the radiation sensitivities of various radiomicrometers for which comparative data are available.

TABLE I

Sensitiveness of Radiomicrometers and Rubens Thermopile

Observer	Full period	Area of vane	Deflections in cm/mm², candle and scale at 1 m
	sec	mm²	cm
Boys	10	4	0.9
Phil. Trans., 180A, p. 159, 1889.			
Paschen	40	....	3.0
Wied. Ann., 48, p. 275, 1893.			
Lewis	20	1.4	1.3
Astrophys. Jour., 2, p. 1, 1895.			
Coblentz This Bulletin, 2, p. 479; 1906.	40 25 16	3 3 5	3.6 (in air) } Bi-Sb 6.0 (in vacuo) } Bi-Sb 5.0 (in vacuo) Bi-Cu
Ibid. 7, p. 248; 1911	50	10 to 12	20.0 in air

With the electrically heated welding device described on a subsequent page (Fig. 1) a much greater refinement in construction and a higher sensitivity should be attainable. With this end in

[11] Duddell: Phil. Mag. (8), 2, p. 91; 1904; Jour. de Phys. (4), 4, p. 5; 1905.
[12] Pierce: Amer. Jour. Sci., 9, p. 252; 1900. Klemenčič, Ann. der Phys. (3), 45, p. 62; 1891.

view, very much smaller and lighter (3 to 5 mg) suspensions should be tried in place of those heretofore employed.

III. THE THERMOPILE

1. BRIEF DESCRIPTION OF THERMOPILES OF RECENT CONSTRUCTION

During the past year or two, numerous attempts have been made to further improve the linear thermopile, principally by the use of finer wires as already indicated.[13] Soon after writing the paper cited above, an investigation was published by Moll[14] in which he used a modified form of Rubens thermopile of 30 elements. The iron-constantan wires were 0.06 mm diameter, the junctions were about 0.2 mm^2 area, the area of the exposed surface being about 0.42 by 11 mm and the resistance about 12 ohms. The galvanometer sensitivity was 1.1×10^{-10} ampere with a complete period of 12 seconds. The weak point in the design of Moll's thermopile arose from joining the "cold" (unexposed) junctions to the heavy metal support instead of having them free as in the original design of Rubens. The hot and the cold junctions, therefore, always had a different temperature (owing to a difference in heat capacity and in emissivity) which caused a large permanent deflection, and a drift in the zero reading. However, by surrounding the instrument with a water-cooled envelope he was able to do excellent work with it.

In passing, attention should be called to a thermopile in the form of an annulus, known as a "coronal thermopile," used by Callendar[15] on a solar eclipse; also to a theoretical paper by Altenkirch[16] on the efficiency of thermocouples, in which he shows that the external resistance can be two to three times the internal resistance of the pile, without seriously affecting the maximum efficiency of the pile.

Paschen[17] constructed a thermopile of iron 0.1 mm and of constantan 0.08 mm in diameter. The constantan wire was 4 mm long. The wires were mounted end to end and fused with a little

[13] This Bulletin, **4**, p. 391; 1908.

[14] Moll: Inaug. Dissertation Utrecht; 1907. Archives Néerlandaises des Sci., Serie II, Tome XIII, p. 100.

[15] Callendar: Proc. Roy. Soc., **77 A**, p. 8; 1905.

[16] Altenkirch: Phys. Zs., **10**, p. 560; 1909.

[17] Paschen: Ann. der Phys., **33**, p. 736; 1910.

borax and silver solder. The junctions and wires were then rolled to 0.002 mm thickness. The number of junctions and the resistance was not given. The maximum temperature was attained in four seconds and 98 per cent of the inrease in two seconds. The sensitivity was about the same as that of a bolometer strip 0.001 mm thickness but was only about one-half that of his best bolometers on high battery current; its manipulation, however, was easier.

Reinkober [18] constructed a vacuum thermopile of 14 junctions of iron-constantan, of wires 0.05 mm diameter and having a resistance of 14 ohms. It was 3 times as sensitive as the old form of Rubens pile with wires 0.15 mm in diameter. In vacuo it was 1.6 times as sensitive as in air. He made also a thermopile (of wires 0.021 mm thickness, hammered thin) of only four elements, since the resistance was 18 ohms. In air, this was twice as sensitive as the old form, and in vacuo 10 times as sensitive as the commercial Rubens instrument. He found that its sensitivity was only one-half that of a vacuum bolometer.

Johansen [19] has made a study of vacuum thermopiles of iron-constantan and of iron-bismuth. From theory he finds that (1) the resistance of the thermopile should equal that of the galvanometer, (2) the radii of the two wires of the element should be so chosen that the ratio between the heat conductivity and the electrical resistance is the same in both, (3) the heat loss by conduction through the wires should equal the heat loss by radiation from the junctions, (4) the radiation sensitivity is proportional to the square root of the exposed surface. In an iron-constantan couple the theory required the use of iron wire 0.023 mm and constantan wire 0.045 mm diameter; and for a Bi-Fe couple iron wire 0.024 mm and bismuth wire 0.075 mm diameter. If the diameter of both wires were twice as great, theory indicates that the sensitivity would be only 0.8 the maximum sensitivity. He used a single long junction consisting of a constantan wire 0.03 mm and an iron wire 0.015 mm diameter soldered to a strip of silver 10 by 0.2 by 0.015 mm. By allowing the radiation to fall on different parts of this long junction he found that the radiation sensitivity

[18] Reinkober: Ann. der Phys., (4), 34, p. 349; 1911. [19] Johansen: Ann. d. Phys. (4), 33, p. 517; 1910.

varied only a few per cent over the whole length. For a junction 0.5 cm long, this variation was 0.9 per cent, which is entirely different from a bolometer strip which has its maximum radiation sensitivity at the middle and zero sensitivity at the ends. He claims that the "temperature sensitivity" of the Rubens pile is 10 to 15 times greater, but that the "radiation sensitivity" is much less than for his instrument. Calling the radiation sensitivity of the Reubens pile 1, then that of his vacuum pile of iron-constantan is 4.5, of Bi-Fe is 9.5 and of his vacuum bolometer is 9.7. The iron-constantan pile required an exposure of 20 seconds and the Fe-Bi pile required 30 seconds to attain a temperature equilibrium.

Spence [20] has recently constructed a sensitive thermopile of two elements (1) an alloy of Bi+5 per cent Sn and (2) Bi+3 per cent Sb. The thermoelectric power was 120 microvolts (iron-constantan = 53). These alloys were pressed into sheets about 0.25 mm in thickness and then cut into bars 2.5 by 0.5 mm. A pile of 37 elements presented an exposed surface of 21 by 0.5 mm. It had a resistance of 5 ohms and a thermal e m f of 4.4 milli-volts per degree. Using a galvanometer having a sensitivity of 4×10^{-10} amperes, a deflection of 1.4 mm (against Rubens = 0.4 mm) would occur for 1×10^{-6} degree rise in temperature. Under this condition a candle at 1 m gave a deflection of 234 cm. He says that a good bolometer would give a deflection of 250 cm under similar conditions. He found the pile sluggish, and it had a slow drift which resulted, no doubt, from the lack of thermal equilibrium of the hot and the cold junctions. This is to be expected, for its heat capacity is almost as great as that of the old type of thermopiles. Moreover, because of this defect, the large temperature sensitivity (120 microvolts per degree per couple) is not a true indication of its radiation sensitivity. The original Rubens pile of 20 junctions of iron-constantan gave a deflection of 250 cm when using a galvanometer about twice as sensitive as the one used by Spence. It therefore appears that, using the same number of junctions, the Spence type of thermopile has no particular

[20] Spence: Phys. Rev., **31**, p. 666, 1910. (See also a paper by Hutchins, Amer. J. Sci., **48**, p. 226, for the alloys used.)

advantage over the one of iron-constantan when a comparison is made of the radiation sensitivity of the two instruments.

The main defect in a thermopile of fine iron wires is the rapidity with which which they rust. They should therefore be given a thin coat of shellac. Since the thermoelectric power of copper-constantan is not markedly different from that of iron-constantan (Fe-Const. = 51 to 53 mv; Cu – Const. = 40 to 41 mv) it seems advisable to use copper instead of iron.

2. CONSTRUCTION OF A BISMUTH-SILVER THERMOPILE

The main defect in a thermopile is its great heat capacity with the consequent lag in attaining temperature equilibrium. This is apparent in nearly all of the designs just described. Furthermore, the more sensitive thermopiles can not be made into commercial instruments.

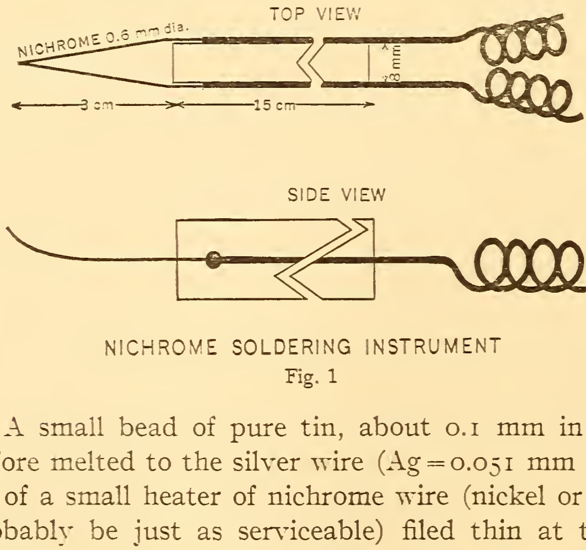
In the instruments now to be described, the success attained in construction results from the use of the electrically heated welding device and from the choice of wire (silver) which is easily freed from sulphide. The silver wire contributes but little thermoelectrically, but this is compensated by its extremely low resistance, which is about 0.07 ohms per centimeter for wire 0.05 mm in diameter. One need not, therefore, exercise any great care in making the silver wires of a minimum length to produce a low resistance thermopile. A preliminary heating brightens and anneals the wire; a procedure which can not be followed in cleaning copper and iron wire. The use of pure tin in welding produces an alloy which is not brittle. The construction of the thermoelements of bismuth and silver is therefore an easy process, so that after attaining some skill they can be made at the rate of 15 to 20 per hour. The instrument can, therefore, be built in any laboratory, and of the proper design to suit the problem under investigation.

(*a*) **Linear Thermopiles.**—An attempt was made to construct a thermopile of bismuth and iron using fine bismuth wire (from Hartmann and Braun) and fine iron wire, and soldering with Wood's alloy. The further addition of bismuth, resulting from melting of the bismuth wire made a very brittle junction. To

make good contact the iron wire was given a coating of pure tin, but that did not appear to remedy the matter. It was very difficult to thoroughly clean the iron wire; and the further difficulty of annealing it made the construction of the thermoelement very laborious. It was found that the resistance of a single junction rose from 1.5 ohms to 3 ohms and sometimes to 90 000 ohms in a few days, so that this type of thermojunction was discarded.

There is no particular advantage in using iron instead of silver, in view of the fact that iron rusts easily; that the Bi-Fe junctions are weak; and that although the thermoelectric power of iron is about 5 times that of silver, its resistance is from 6 to 10 times that of silver.

The welding of bismuth to silver makes a very strong junction. It was found that the direct welding of bismuth to silver was



NICHROME SOLDERING INSTRUMENT

Fig. 1

difficult. A small bead of pure tin, about 0.1 mm in diameter was therefore melted to the silver wire (Ag = 0.051 mm diameter) by means of a small heater of nichrome wire (nickel or iron wire would probably be just as serviceable) filed thin at the point, shown in Fig. 1. The end of the bismuth wire (0.1 mm diameter) was then brought in contact with this bead of tin (probably an alloy of Sn and Ag) which is then melted with the nichrome heater. Such a heater is better adapted to delicate work of this type than is a well-tinned soldering copper, the surface tension of the molten material on the hotter surface of an ordinary soldering instrument being sufficient to tear fine bolometer strips. The

bismuth wire is too brittle to permit flattening the junction, so that a small rectangle of pure tin 1.4 by 0.6 by 0.025 mm was then placed under the Bi-Ag junction and fused thereto with a light touch of the nichrome heater. It is somewhat easier to flatten the tin bead attached to the silver and then fuse the bismuth to this flat disk, as shown in the lower part of Fig. 2, but in this case it is not so easy to produce a receiving surface which completely fills the thermopile slit.

There are many points in favor of the use of silver instead of copper wire in this type of thermopile. It is easily annealed and the tarnish is easily removed by heating the wire on a sheet of metal. Thus cleaned the bead of tin is attached without any soldering acid. A bit of rosin is useful but not necessary in attaching the bismuth wire. The low resistance, and especially the pliability of the silver are also important advantages, which one appreciates after working with (unannealed) iron and constantan wires. The bismuth wire is not so pliable but it is short and, since it is subject to but little handling in mounting, is not liable to be broken.

Before mounting, each junction was given a thin coat of shellac on the rear side for insulation, and the front surface was painted with a mixture of equal parts of lampblack and chemically precipitated platinum black in a dilute alcoholic solution of shellac. The amount of shellac to be added is just sufficient to cause the material to adhere well to the metal surface. This produces a hard, compact, matte surface which permits the removal of dust. The platinum black increases the thermal conductivity. Using receivers of equal size, it was found that the radiation sensitivity of the receiver covered with the mixture of lampblack and platinum black was 1.5 as great as the one painted with pure lampblack. This is a question which requires further investigation.

The junctions were then mounted upon a glass plate with Le Page's glue, the edges slightly overlapping, as shown in the upper part of Fig. 2, and the ends of the silver wires were soldered together. The glass plate was then mounted on an ivory frame and the loose ends of the silver wires were attached to the latter with shellac after which the glass plate was removed by soaking in water, thus

leaving a uniform, solid, well-insulated receiver, as shown in Fig. 3. Subsequently, all these junctions were separated and the resistance of the pile was then found the same as when the junctions were in contact, showing that the insulation was perfect. The silver wires were then given a thin coating of shellac, but this is not necessary. The length of the receiving surface of this pile of 20 junctions is 12 mm. The great width, 1.3 to 1.4 mm, of this particular pile was chosen for a special research which required high sensitivity. The rectangles or disks of tin could be made much smaller as in the new form of Rubens thermopile.

The thermal emf of this bismuth-silver thermocouple is 89 microvolts per degree as compared with 51 to 53 microvolts for an iron-constantan couple. The temperature sensitivity of Bi-Ag is

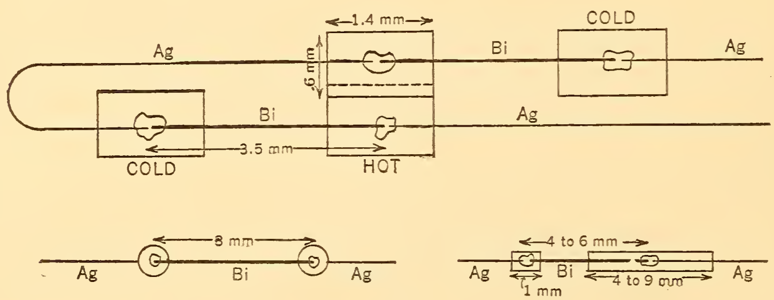


Fig. 2

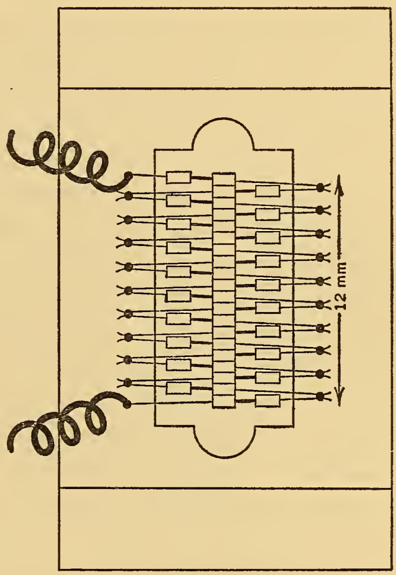
therefore about 71 per cent greater than that of an iron-constantan thermopile. Whether the radiation sensitivity is increased in like proportion depends upon the selection of the proper diameters of wires. As shown later, the radiation sensitivity of this thermopile is 2.5 to 3 times that of the iron-constantan pile. The new form [21] of iron-constantan thermopile of fine wires has a resistance of about 9 ohms. The above thermopile of bismuth-silver has a resistance of 9.3 ohms. By using bismuth 0.6 mm diameter the resistance would be much higher.

The radiation sensitivity of this bismuth-silver pile and of an iron-constantan pile were compared, by means of a galvanometer of 5.3-ohms resistance and a sensitivity of 4.6×10^{-10} ampere.

[21] This Bulletin, 4, p. 391; 1908.

Using first the bismuth-silver pile, a standard sperm candle placed at a distance of 2.4 m caused a deflection of 10.2 cm (or 59 to 60 cm for a candle and scale at 1 m). With a galvanometer sensitivity 3 times as large as ordinarily used, the total deflection (in air) would have been about 180 cm. This is only about one-half as sensitive as the vacuum bolometer to be described presently, but in vacuo it would be as sensitive as the vacuum bolometer.

The Rubens iron-constantan thermopile, with wires about 0.15 mm in diameter and having a resistance of 4.7 ohms similarly exposed, caused a deflection of 3.8 to 4.0 cm (or about 23 cm for a candle and scale at 1 m). The receiving surfaces of this pile were about 1.5 mm diameter and about 0.2 mm thick. The disks overlapped so that the 20 junctions occupied a space 20 mm long. The actual area exposed was therefore greater than in the Bi-Ag pile, which had a receiving surface of about 16 mm². This comparison shows that the radiation sensitivity of the bismuth-silver is about 2.6 times that of the ordinary Rubens thermopile. If we consider that in spectroradiometry we are interested in the length of the spectral line which can be utilized, we should have made the length of the Bi-Ag pile 20 mm, by adding more couples. The radiation sensitivity of the Bi-Ag pile would therefore be increased in the ratio of 20 to 12, which would give a total deflection of about 100 cm instead of 60 cm as observed. It is therefore safe to say that, comparing equal lengths of receiving surface utilized on a spectral line, the radiation sensitivity of this type of bismuth-silver pile is 4 times that of the old type of low resistance, iron-constantan pile. If we compare the bismuth-silver with the



Bi-Ag THERMOPILE

Fig. 3

fine wire type [22] of iron-constantan pile, which has a resistance of 8.9 to 9.3 ohms and a radiation sensitivity 1.4 times that of the old type of Rubens pile, it is a fair estimate to say that this bismuth-silver pile has a radiation sensitivity at least 3 times as great as the new type of iron-constantan thermopile.

One important point usually not considered is the heat capacity and hence the speed of attaining temperature equilibrium in these instruments. In the present radiation sensitivity tests the half period of the galvanometer was 2 seconds. When joined with the bismuth-silver pile the half period was lengthened to about 3.8 seconds, which is practically the same as with the new type of fine-wire iron-constantan pile described in a previous paper.[22] This is not an excessively long period and the galvanometer mirror returns quickly to its zero position. With the old heavy-wire type of iron-constantan pile, the time of single swing of the galvanometer was increased from 2 seconds to about 6.5 seconds and there was a tendency to lag, especially when measuring intense radiation, so that it does not compare favorably with the bismuth-silver pile.

This thermopile of bismuth-silver was designed for special work requiring a large receiving surface in air where very thin metal is easily affected by air currents. The hot and the cold junctions are sufficiently alike in size and emissivity so that no temperature difference and consequent drift is produced in the galvanometer deflection. The junctions are easily made and mounted, and are equally easy to repair if broken. The iron-constantan pile of fine wire is difficult to handle and difficult to repair if broken.

By using an alloy of platinum-iridium instead of silver the thermoelectric power would be increased, but owing to the increased resistance it remains to be determined whether a higher radiation sensitivity would be obtained.

The present instrument is not intended for rapid work, but to give exact and undisturbed readings with the instrument in air. The time to attain temperature equilibrium is about 4 seconds, but by reducing the heat capacity (using finer bismuth wire) temperature equilibrium should be attained in less than 3 seconds. In another comparison test, using a more intense radiation (acetylene flame), the bismuth-silver pile attained temperature

[22] This Bulletin, 4, p. 391: 1908.

equilibrium in 6 to 7 seconds, while the Rubens pile required from 25 to 30 seconds. The two piles being similarly mounted, one can assume that this is owing to the great difference in the heat capacity of the two kinds of thermojunctions.

The logical procedure in this investigation would have been to test various combinations of bismuth and silver wires before constructing a thermopile; but the marked success attained was not anticipated, and the following experiments were made on silver wire procured afterwards.

In the experiments on surface thermopiles, to be described presently, it was found that bismuth wire 0.15 mm diameter has a too great heat capacity, so that half a minute was required to attain thermal equilibrium, and that bismuth wire 0.1 mm diameter was very satisfactory. The question, therefore, to be solved was the size of the silver wire to be used with 0.1 mm bismuth wire in order to attain the maximum radiation sensitivity. The dimensions of the tin receivers were 2.5 by 0.03 mm. All the comparisons were made against a standard junction, A, with silver wire 0.0513 mm in diameter; the other junction, B, being made with silver wire of small diameter, say, 0.04 mm. The intervening bismuth wire was about 4 mm long. These elements were mounted over an opening in thick cardboard and covered with glass plates to avoid air currents. The source of radiation was an acetylene flame, and the comparison was made by exposing alternately the standard junction, A, of 0.05 mm silver wire and the one under investigation, B.

Using an element with silver wire, $B = 0.0410$ mm diameter, the ratio of sensitivities $B \div A$ was 1.13. In other words, a thermopile, in which the bismuth wire is 0.1 mm diameter and in which the silver wires are 0.04 mm diameter, would have a radiation sensitivity which is about 13 per cent higher than the one just described of silver wires 0.05 mm diameter. The latter contains about 20 cm of silver wire having a resistance of about 1.4 ohms, the total resistance of the pile being about 10 ohms. The total resistance of a pile of 20 junctions having silver wire 0.04 mm diameter and bismuth 0.1 mm diameter would therefore be from 11 to 12 ohms.

Using an element with silver wire, $B = 0.030$ mm, the ratio of sensitivities $B \div A$ was 1.20. The two receivers were then re-

blackened and the ratio was 1.195. In a vacuum the sensitivity was doubled by reducing the pressure to about 0.15 mm. With a lower pressure the sensitivity would of course be still further increased. A pile of 20 elements having silver 0.03 mm in diameter would have a radiation sensitivity about 20 per cent higher than the one herein described, and its resistance would be from 13 to 14 ohms.

Using silver wire 0.021 mm diameter, the ratio of B ÷ A was 1.12. The same value was obtained on repainting the receivers. The resistance of such a pile of 20 elements would be from 18 to 19 ohms. Its radiation sensitivity in air would be about the same as that of a pile having silver wires 0.04 mm diameter, and hence there is no advantage in using the finer wire. The loss by convection is usually found to be greater from fine wire so that, in a high vacuum, the radiation sensitivity might be considerably increased when using a small receiver and fine silver wires. In the present tests the sensitivity was increased 70 per cent in a vacuum of about 0.15 mm pressure. This increase in sensitivity is somewhat less than found in the element having 0.03 mm silver wire. These tests show that the size of the wire is not an important factor at this gas pressure.

From the aforesaid experiments it appears that the most sensitive thermopile of bismuth wire 0.1 mm diameter is obtained by using silver wire 0.03 mm in diameter. It appears advisable, however, to apply a coat of lacquer to wires of this fineness to avoid a change in resistance, which may result from tarnishing of the wire.

(*b*) **Surface Thermopiles.**—The success attained with the linear pile led to the construction of a thermopile having a large receiving surface, built up of single units, each of which contains 20 or more thermoelements mounted upon an ivory support as shown in Fig. 4, C. In the preliminary tests to determine the most desirable width of strip to be used, thermoelements were built with receivers of the same width, 0.6 mm, and of different lengths, as shown in the lower part of Fig. 2. In all cases the silver wire used was 0.0513 mm diameter. The bismuth wires (4 to 5 mm long) were 0.06 and 0.15 mm in diameter. The two receiving surfaces (1 by 4 mm, or 1 by 9 mm) were blackened, and exposed alter-

nately to radiation. The elements to be tested were inclosed in order to avoid air currents.

Using bismuth wire 0.15 mm in diameter, the deflection for a receiver 4 mm long was not quite twice that of a receiver 1 mm long. For both receivers the deflection did not attain a maximum abruptly; and there was a serious creeping, requiring some 15 seconds for the galvanometer to come to rest.

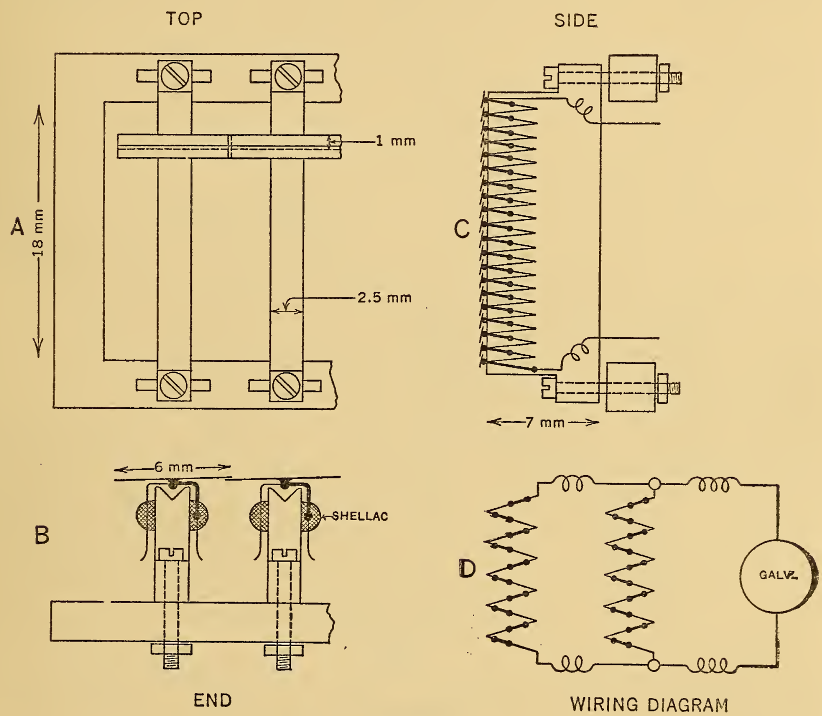


Fig. 4

Using bismuth wire 0.06 mm in diameter, the galvanometer deflection for a receiver 4 mm long was 2.1 times as large as that for a receiver 1 mm long. On reducing the length of the 4 mm receiver to about 2.6 mm, the sensitivity was 1.9 times as great as for the receiver 1 mm in length. A receiver 9 mm long was 2.7 times as sensitive as a receiver 1 mm in length. As shown in Fig. 5, the sensitivity varies roughly as the square root of the receiving surface, which is the law of the surface bolometer. As a matter of

fact, there is an optimum length, which is of the order of 2 mm, but the exact value was not determined. Obviously, two receiving surfaces 4 mm wide are better than a single one 9 mm wide in the ratio 4.2 to 2.7. In fact, the sensitivity should be still greater than this (if a galvanometer having a resistance of the same magnitude be provided), for by placing the two units (4 mm wide) in parallel, the internal resistance is reduced to one-half the former value. Units which are built up with receiving surfaces 4

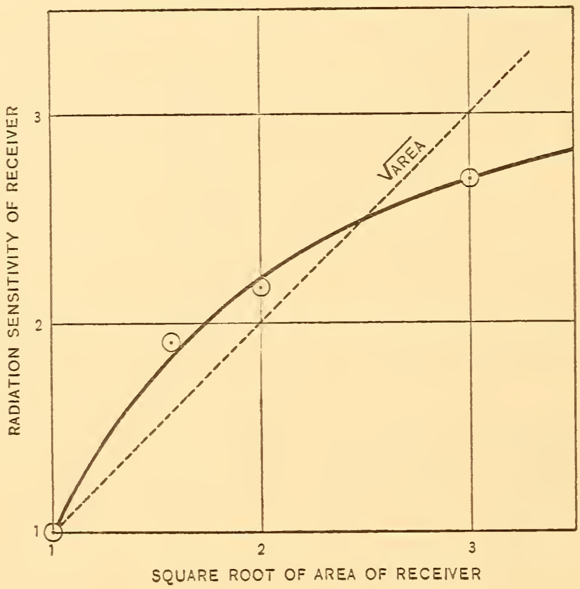


Fig. 5

to 6 mm wide give ample working space in mounting, so that there is a distinct gain in using such narrow widths.

No difference could be detected in the sensitivity of the front and the rear surfaces of these junctions, showing that attaching the junction at the center of the receiver is not detrimental.

The size of the receiver made no appreciable difference in the time of attaining a temperature equilibrium. In constructing a surface thermopile for experimental tests it was therefore deemed permissible to omit the receiving surfaces from the unexposed junctions. The results show that unless the instrument is well

shielded, there may be drift as found by Moll. With the fine bismuth wire the deflection attained its maximum abruptly in 3 to 4 seconds.

In a vacuum of 0.15 mm pressure, the thermoelement of bismuth wire, 0.06 mm in diameter, was 2.03 times as sensitive as in air. The sensitivity would be further increased in a higher vacuum. It is, therefore, a distinct advantage to place the pile in an evacuated inclosure.

Using receivers of the same size, the radiation sensitivity of a thermoelement of bismuth wire 0.15 mm (and silver wire 0.05 mm) in diameter was twice as great as that of an element of bismuth wire 0.06 mm in diameter, as indicated by theory.[23] But the serious lag in attaining temperature equilibrium in a thermopile of bismuth wire 0.15 mm in diameter is objectionable, so that it is to be recommended only where a very high sensitivity is required and where the radiation to be measured is very weak.

In the surface thermopile it was therefore decided to use bismuth wire 0.1 mm and silver wire 0.05 mm in diameter, which increases the radiation sensitivity to nearly that of an element with bismuth wire 0.15 mm in diameter, while the time of attaining temperature equilibrium is about the same as that of the element having bismuth wires 0.06 mm in diameter. If the various elements are joined in parallel, as shown in Fig. 4, D, the resistance is reduced and the sensitivity is increased. By having the units uniformly exposed to radiation, so that each unit produces the same voltage, there will be but little shunting of the current generated. It is therefore important to have the units of the same heat capacity and emissivity, equality of resistances being of minor importance.

In making the units, the insulated, blackened, individual elements are mounted in a row, upon a glass plate, as previously described for the linear pile, and the silver end wires are soldered together. The ivory support is then placed over the central line of receivers, and the end wires are bent back against the side of this support (shown in Fig. 4, B, C) and attached thereto, along the side, with shellac. No shellac is permitted to come in contact with the "hot" junction, which would affect the heat capacity.

[23] Johansen: Ann. d. Phys., (4) **33**, p. 517: 1910.

The sensitivity and heat capacity are not affected by having this junction in contact with the ivory support. In the latest design, however, the active junction is suspended across a slot in the ivory support. The mounting of the elements is the most delicate part of the work, as the bismuth wires become brittle after bending them several times. Since the wires are bent away from the receiving surface, before mounting (Fig. 4, B), in order to apply the insulating coat of shellac on the rear surface, it is best to leave them thus throughout the remainder of the construction. A small bead of solder is attached to the end of each one of the silver wires before mounting the elements on the glass plate, and it is then an easy matter to connect them with the nichrome heater. It is necessary, however, to hold the wires with tweezers to prevent heat from being conducted to the bismuth, which would melt the junction.

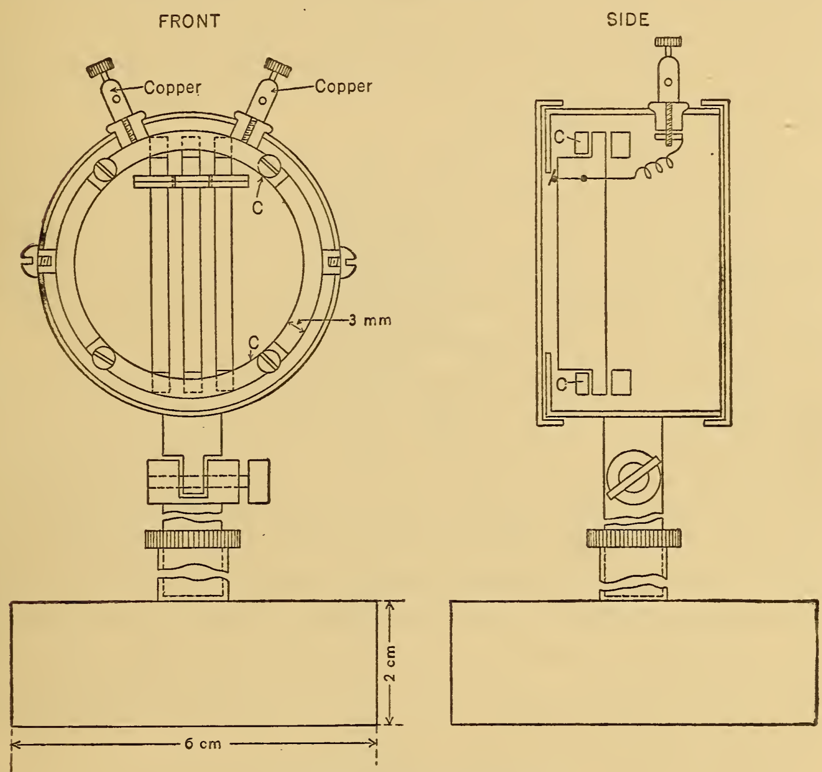
After the shellac has dried, and the pile has been separated from the glass plate by soaking in water, the elements are very securely held to the ivory mounting and there is little danger of breaking them. Because of the fragility of the bismuth wire, in mounting it might be better to use a different form of holder than the one here described, and join the bismuth-silver junction to the tin receiver as shown in Fig. 7, C.

The mounting for these ivory supports (Fig. 4, A) may be of brass, and, for convenience in construction, may be circular, as shown in Fig. 6. The slight adjustment of the ivory supports, necessary in placing them upon this mounting, is accomplished by means of slots and bolts, as shown in Fig. 4, A, or by means of clamps, *e*, as shown in Fig. 6. In Fig. 6 is shown a surface pile made of three units each consisting of 20 elements. The individual receivers are of tin 6 by 1 by 0.03 mm, and the total area is about 17 by 17 mm. The instrument was designed for psychological work, in which it is desired to measure a light stimulus 15 mm in diameter.

The three individual units have closely the same resistance and the same radiation sensitivity; but in overlapping them to form a continuous surface there is no doubt a slight loss in sensitivity. With the short period galvanometer used, it could not be deter-

mined whether there was a difference in the time required for each of the three units (joined in parallel or series) to come to thermal equilibrium. This would cause the galvanometer deflection to approach a maximum at an irregular rate.

Using the three units in series (resistance 33.6 ohms), and a galvanometer resistance of 5.3 ohms and $i = 6.5 \times 10^{-10}$ ampere, a



HOLDER FOR THERMOPILE

Fig. 6

standard sperm candle at a distance of 3 m gave a deflection equivalent to 166 cm at 1 m. For a galvanometer sensitivity of $i = 2 \times 10^{-10}$ ampere, as ordinarily used, this would be about 560 cm deflection for a candle and scale at 1 m. This is about 4.2 times the deflection of the aforesaid linear pile used under similar conditions. It attained thermal equilibrium in the same time

(in 2.5 to 3 seconds, for a galvanometer half period of 1 second) as obtained with the linear thermopile.

With the three units joined in parallel (resistance 3.8 ohms) and with a galvanometer sensitivity of 6.8×10^{-10} ampere, the deflection for a candle at 2 m was equivalent to 227 to 230 cm at 1 m. For a sensitivity of 2×10^{-10} ampere this would correspond to 770 to 780 cm for a candle and scale at 1 m. This is about 6 times (the values, obtained on different days, varied from 5.9 to 6.05) the sensitivity of the linear pile. The galvanometer half period was increased from about 1 second to 3 seconds when the pile was exposed to radiation.

From a consideration of the areas of the individual receivers, the surface thermopile should have been 7.3 to 7.5 times as sensitive as the linear pile. In view of the fact that this is the first instrument of the present type of surface thermopile ever constructed, the agreement between theory and experiment (experiment $= \frac{6}{7}$ theory) is fairly satisfactory.

As shown on a previous page, by using finer silver wire (silver 0.03 mm, bismuth 0.1 mm) the radiation sensitivity would be increased 40 to 60 per cent. Expressed in terms of the Rubens linear pile, it is a fair estimate to rate the surface thermopile of bismuth silver (17 by 17 mm) at from 15 to 20 times the sensitivity of an iron-constantan thermopile. In such researches as can be performed with the thermopile inclosed and evacuated to 0.1 mm pressure (thus obviating the unsteadiness caused by air currents) the sensitivity attainable is at least twice this value. In fact high precision work can not be done with these instruments in open air; and hence the inclosing vessel might as well be one that may be evacuated, thus doubling the sensitivity.

From the data just cited, it may be seen that when the three units were connected in series the internal resistance was about 6.4 times the external (galvanometer) resistance; and the radiation sensitivity was about two-thirds that of the thermopile having the units joined in parallel, and having a resistance of 3.8 ohms. From this it appears that the external resistance may be considerably different from the internal resistance without seriously affecting the radiation sensitivity.

Obviously, the sensitivity to be attained depends upon the number of units, and this depends upon the skill and patience one has in constructing such instruments. From the tests made thus far, there appears to be a small permanent emf (resulting probably from the difference in emissivity of the hot and the cold junctions), but it causes no annoyance other than displacing the galvanometer deflection several centimeters on closing the circuit. In the linear

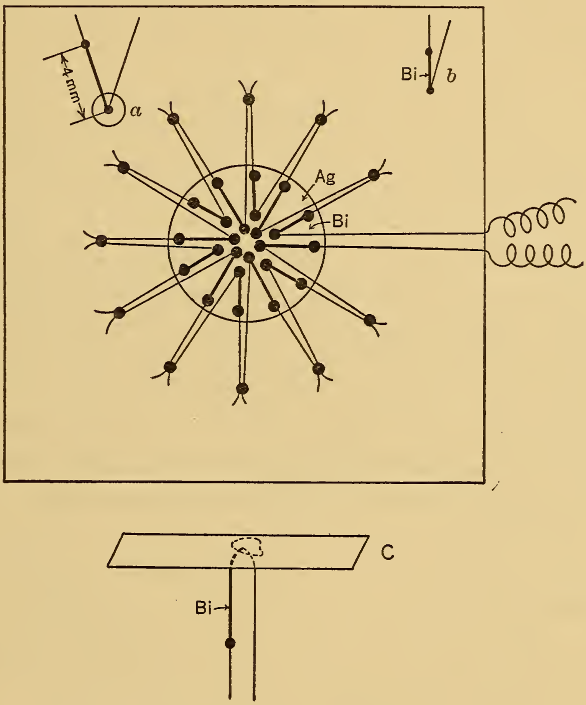


Fig. 7

pile this is obviated by having the two sets of junctions covered with receivers which are suspended in air.

In Fig. 7 is shown a point source (receiver) thermopile which is useful in measuring radiation confined in a small circular area. The individual junctions (Fig. 7, a) are made by attaching a small bead of tin to the silver wire, hammering it thin (1 mm diameter), fusing the bismuth wire thereto, painting the rear side with shellac,

blackening the front side, and then mounting the same (overlapping) upon a sheet of mica having a central opening 1 cm in diameter. This thermopile consists of 16 elements joined in series, and has a resistance of 10 ohms. The central pile of receivers presents a continuous surface 4 mm in diameter. Mounted as a photometer, this instrument may be used in comparing the intensities of light sources.

Another point receiver thermopile of 10 elements, suitable for star images, sun spots, etc., was constructed of bismuth wire 0.04 mm and silver wire 0.019 mm diameter. The fine wires were made, from the material previously described, by reduction in nitric acid. The receivers were constructed as shown in Fig. 7, b the active junctions being insulated with a thin coat of shellac. Back of these junctions, but not in metallic contact with them, was placed a disk of tin 1 mm in diameter and 0.01 mm in thickness. The rear side of this disk was left bright; and the front side, including the active junctions, was covered with the lampblack and platinum black combination already described. The active junctions occupied only a portion of the disk. The resistance (tested before and after the junctions were placed in contact with the disk) was 19.3 ohms. The bismuth wires were 3 mm long, but for weak sources, such as star images, the length of the bismuth wire could be reduced to 2 mm, thus reducing the resistance to about 12 ohms. When used with a gavlanometer of 5.3 ohms resistance, half period of 3.5 seconds and sensitivity of 2×10^{-10} ampere, the deflection for a standard sperm candle and scale at 1 m was from 61 to 62 cm. From the experiments described on a previous page, this value should be increased from 20 to 25 per cent, owing to the difference in resistance of the thermopile and the galvanometer. In practice one would provide a more suitable galvanometer, and the deflection would therefore be 75 to 76 cm per meter candle.

The Nichols radiometer, used for measuring heat from stars, gave a deflection of 52 cm per meter candle when used on a complete period of 11 seconds. A magnetically shielded galvanometer is easily operated with this or even a greater period; and since thermopiles and radiomicrometers of the abovementioned sensitivity should be operated in inclosures exhausted to 0.1 mm pressure, which doubles the sensitivity, it appears feasible to produce

a radiometer having at least 4 times the sensitivity previously employed in measuring the radiation from stars.

Point receivers of this type would be useful in radiation pyrometers (Fery's) which are now made with but one thermo element.

These surface thermopiles, built as they are on a small scale, foreshadow the possibilities which the future may bring forth in the form of large receiving surfaces, similar in principle but of somewhat different design, which, by utilizing (solar) radiation, will generate sufficient current to operate relays, recording devices, etc.

By placing a surface thermopile (single unit of 20 or more junctions) back of the manganin heater in an Ångström pyrheliometer, but not in contact with the heater, as now obtains, it is hoped to obtain a more reliable instrument for measuring radiation in absolute measure.

In Fig. 8 is shown a double-walled case for a (linear) thermopile. It is modeled after the bolometer case described in the previous paper, and consists of three parts: (1) The tube with diaphragms, (2) the main double-walled jacket, and (3) the end piece which supports the thermopile from three rods, R. The latter may be rotated about a horizontal axis to adjust the thermopile slit upon a spectral line, and then is clamped by the nuts, K. The metal disk, Fig. 8, A, supports the adjustable slit, c, c, and the thermopile, T.

For adjusting the slit upon a spectral line, the eyepiece, with a right-angled prism, is pushed down in front of the slit; the fine adjustment being made by means of a micrometer screw, S, which rotates the case about the screw, D, as an axis. Experiments show that unless the water supply is of uniform temperature it is better to have it stand in the jacket surrounding the radiometer rather than to have it flowing. In this laboratory it has been found sufficient to use a double-walled jacket containing an air space about 1 cm in thickness.

The sensitivity of a surface bolometer varies as the square root of its surface. The aforedescribed linear thermopiles have practically the same sensitivity as linear bolometers, but their surface sensitivity does not follow the square-root law, there being an optimum value which, on the dimensions tested, was 20 per cent

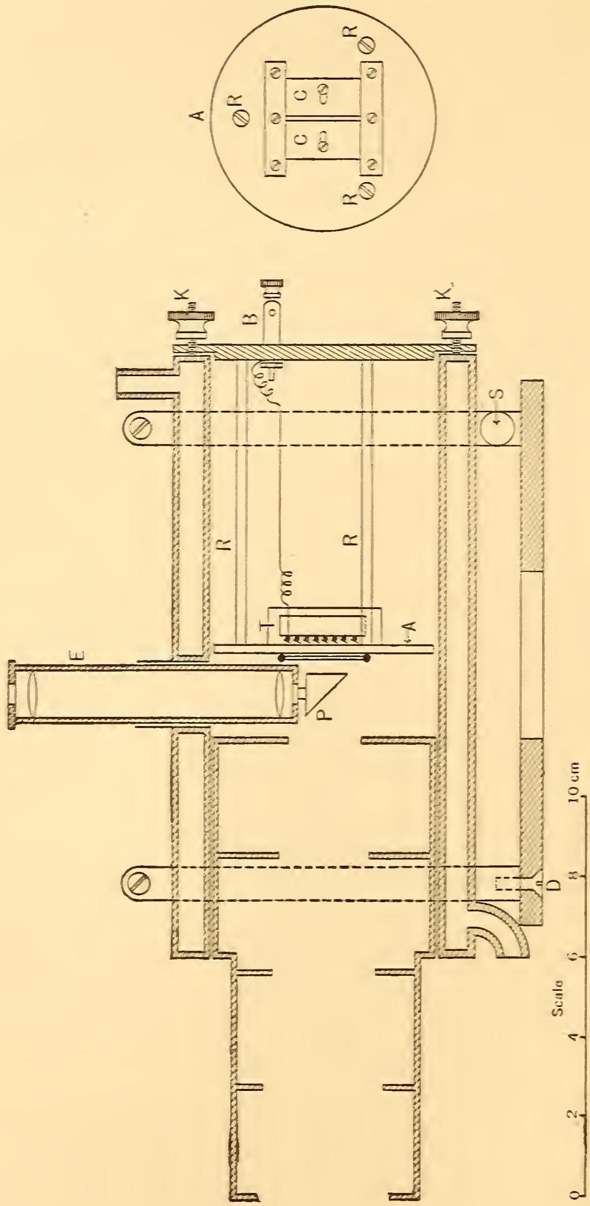


Fig. 8

greater than the square-root law. Hence, if one has the patience to construct such an instrument it seems possible to obtain a surface thermopile which has a higher sensitivity than a surface bolometer. Unfortunately at this writing no good surface bolometers were at hand to make this comparison.

(*c*) **Thermopile-Galvanometer Sensitivity Testing Device.**—In places where the galvanometer and (air) thermopile can be kept at a uniform temperature it is most convenient to test the galvanometer sensitivity by passing a known current through it. For this purpose it is desirable to have the galvanometer connected with the thermopile by means of a two-way switch. This enables the operator to throw the switch at will from the thermopile circuit to the battery circuit. When the galvanometer is adjusted to a high sensitivity this operation may seriously displace the zero of the scale reading. It is therefore desirable to test the galvanometer with the thermopile circuit closed. For this purpose an auxiliary coil of wire is placed in a fixed position near the galvanometer coils through which a known current is passed. This will cause a deflection which is proportional to the current sensitivity of the galvanometer. The relation of the current sensitivity of the galvanometer to the sensitivity as defined by this arbitrary standard may easily be determined by passing a known current through the galvanometer coils. If the thermopile is used in vacuo, a standard source of radiation should be used in testing the sensitivity.

In conclusion, it is desirable to add a word of caution in regard to the use of these surface thermopiles, for we are confronted with a difficulty not usually encountered, viz, a possible drift [24] of the galvanometer if the thermopile is not well shielded and the shutter is not kept at a uniform temperature.

It is therefore important to have the hot and cold junctions of the same emissivity and heat capacity. To this end it seems advisable to attach "receivers" to both the hot and the cold junctions. To the latter the receivers may be attached by means

[24] A surface bolometer is subjected to the same disturbances, in addition to air currents caused by the heat generated by the battery current, but the drift can be balanced by means of a slide wire.

of low melting point (Wood's) alloy, shellac, or an amalgam such as used by dentists, after the instrument is completed.

The quickest way to balance the drift in the thermopile circuit is to alter the position of a magnet placed near the galvanometer, the sensitivity being tested, as already mentioned, by an auxiliary coil placed on the galvanometer. Another method for keeping the galvanometer reading adjusted would be to place a coil of wire near the galvanometer and pass a current through it in the proper direction to cause a deflection in the opposite direction to that caused by the drift of the thermopile. By varying the distance of the coil from the galvanometer or the current through the coil, or both, a balance may be brought about just as in the surface bolometer. Not having as yet experienced any of these difficulties in this laboratory, these suggestions are given in anticipation of what may be encountered by others whose problems may not admit of thorough protection of the thermopile from temperature variations.

IV. THE BOLOMETER WITH ITS AUXILIARY GALVANOMETER [25]

In the present paper only the most important of the recent improvements of this instrument are discussed. Until recently the notion prevailed that the bolometer, in vacuo, is difficult to operate; but the advances made during the past few years indicate that, whenever the investigation admits of it, bolometers, and in fact all the aforesaid radiometers, should be operated in a vacuum of not more than 0.1 mm mercury pressure.

1. HISTORICAL SUMMARY

One of the recently described galvanometers is Paschen's,[26] which, for a period of 10 seconds and a resistance of 1 ohm, has a sensitivity of about 2.5×10^{-10} ampere.

Nichols and Williams [27] have described a convenient galvanometer with an excellent magnetic shield. The galvanometer had 4 coils of wire, each 2.6 cm diameter. Each coil was wound in 3 sections; 81 cm of No. 38, 328 cm of No. 32, and 1318 cm of No.

[25] The notes on the auxiliary galvanometer are given in Appendix I.

[26] Paschen: Ann. der Phys. (4), 33, p. 738; 1910.

[27] Nichols and Williams: Phys. Rev., 27, p. 250; 1908.

26 wires; resistance, 5.6 ohms (1.4 for the 4 coils in parallel). The magnet system consisted of two groups of 7 needles each, of tungsten steel wire 0.165 mm diameter and 2 mm long. The sensitivity was 4×10^{-10} volt for 1 mm deflection for a complete period of 6 seconds. Of chief interest are the cylindrical shields of silicon steel, which had a shielding ratio 40 times as great as the best form designed by Du Bois and Rubens. Using 3 of these shields, designed according to the computations of Wills,[28] the "shielding ratio" was 2903 for the unannealed, and 4274 units for the annealed cylinders. Five shields of soft-iron water pipe gave a shielding ratio of 2725, and with a later design 6 shields of annealed water pipe gave a shielding ratio of over 9000.

Trowbridge [29] has used a similar outfit including a vacuum spectrobolometer, in which the bolometer and the optical parts of the spectroscope are evacuated.

Seddig [30] has described an "absolute bolometer" in which two branches have a positive and two branches have a negative temperature coefficient. He uses iron and carbon for the branches. The novelty in the device is the use of carbon and the exposure of the four branches to radiation, but, from tests made on the commercial instrument, it does not seem to justify the claims made for it. The iron is of course too short lived, owing to oxidation, and the "absolute" measures can be made only after calibration against a known source of radiation. In this respect all instruments may be calibrated to read in absolute units.

Leimbach [31] has used extensively a linear "absolute bolometer" constructed on the double-bridge principle described by Paalzow and Rubens.[32] The area of the bolometer strips was 0.63 mm^2 (two strips 0.025×12 mm), resistance 165 ohms, and thickness 0.00028 mm. He used an Edelmann string galvanometer, the sensitivity of which was 7.4×10^{-10} amp. In the radiation sensitivity test he used a Du Bois-Rubens galvanometer having a period of 10 seconds. (The current sensitivity was not given.) The deflection was about 200 cm for a candle and scale at 1 m, which is a high sensitivity.

---

[28] Wills: Phys. Rev., **24**, p. 243; 1907.
[29] Trowbridge: Phys. Rev., **27**, p. 282; 1908. Phil. Mag. (6), **20**, p. 768; 1910.
[30] Seddig: Phys. Zs., **10**, p. 533; 1909. Ver. Phys. Gesell., Berlin, **13**, p. 53; 1911.
[31] Leimbach: Zs. für Wiss. Photogr., **7**, p. 152; 1909. Ann. der Phys. (4), **33**, p. 308; 1910.
[32] Paalzow and Rubens: Ann. der Phys. (3), **37**, p. 529; 1899.

Warburg, Leithauser, and Johansen [33] have made important contributions to the study of vacuum bolometers, and their complete paper should be consulted. They studied bolometers varying from 0.2 to 1.0 mm in width, and found that in the vacuum bolometer the heat lost by radiation is proportional to the third power of the temperature. In a vacuum bolometer the maximum radiation sensitivity is proportional to the square root of the width of the bolometer, while for an air bolometer the sensitivity is proportional to the width. The heat lost by air conductivity for a bolometer 1 mm wide is 4.5 times, and for a bolometer 0.2 mm wide it is 14.8 times as great as the loss by radiation. The internal heat conductivity reduces the radiation sensitivity of an air bolometer by 15 per cent and that of a vacuum bolometer by 38 per cent.

The radiation sensitivity of a vacuum bolometer was found to be proportional to the current for small values, but for a large current the radiation sensitivity of a narrow bolometer passes through a maximum. This maximum is attained for a current density at which the radiation sensitivity of the air bolometer does not depart appreciably from proportionality with current. A vacuum bolometer 0.2 mm wide was found to be 10 times as sensitive as it was in air, when used in a small current, but only 5 times as sensitive when in both cases the current was raised to its highest operating value. This is of practical importance when one is limited to a given galvanometer sensitivity.

The manner in which the radiation sensitivity varies with the gas pressure and with the bolometer current is well shown in Fig. 9 which is taken from a paper by Buchwald.[34] In this illustration the ordinates represent the galvanometer deflections when the bolometer was exposed to a source of radiation. The various curves represent different gas pressures. In this experiment the bolometer was 0.15 mm wide. Using a bolometer 0.5 mm wide the curves (see Fig. 11) do not come to such a sharp maximum as the ones shown in Fig. 9.

---

[33] Warburg, Leithauser, and Johansen: Ann. der Phys., 24, p. 25; 1907.

[34] Buchwald: Ann. der Phys. (4) 33, p. 928; 1910.

2. THE CONSTRUCTION OF SENSITIVE BOLOMETERS

In the bolometer the sensitiveness is closely proportional to the square root of the surface, so that in spectral energy work, where the bolometer strip is narrow, the sensitiveness attainable through the bolometer is limited.

Since writing the previous paper the present instrument has been considerably changed, and the experience gained indicates that in air bolometers it is not advisable to use platinum which is much less than 0.001 mm in thickness. The methods of mounting are as before described. In mounting the bolometer strips on the

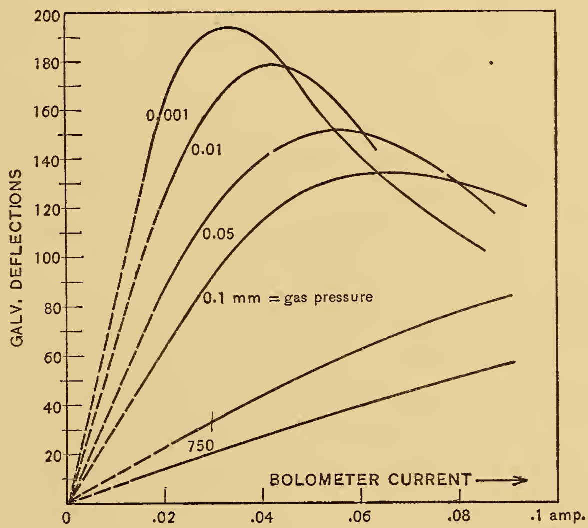


Fig. 9

holder, the one exposed to radiation is first soldered in place, using rosin for a flux. The unexposed strip is made a little longer, so that it will have a slightly greater resistance, which by subsequent resoldering is made equal ro that of the exposed strip. This is a difficult task when using very thin bolometer platinum. In one of the latest bolometers (No. 9; 0.0003 mm thickness) consisting of platinum strips 10 by 0.6 mm, the resistance of the exposed strip is 6.447 ohms and of the unexposed strip is 6.459 ohms. But the risk of breaking is too great to balance to such a nicety

and in the vacuum bolometer, known as No. 10, to be described presently, the bolometer strips are balanced to 1 per cent.

The question of a satisfactory slide wire for balancing the bolometer has required considerable attention. It was found that the constantan slide wire became soiled and required frequent polishing. In the latest design of vacuum bolometer the mercury contact previously described is used in connection with slide wires of platinum which are 0.5 and 1 mm in diameter.

3. COMPARISON OF SENSITIVENESS OF VARIOUS BOLOMETER-GALVANOMETER COMBINATIONS

Important data on sensitive radiometers, and particularly that relating to bolometers, were given in Table IV of the previous paper. It will be noticed that the bismuth-silver thermopile is as sensitive as the air bolometer. In the previous paper it was shown that the temperature sensitiveness of the various instruments falls in two groups. To the first group belong the earlier instruments of Rubens, of Snow, and of Paschen, with a sensitiveness of about 5×10^{-5} degrees per mm deflection. To the second group belongs a more sensitive combination of Paschen's and the writer's vacuum bolometer, in which 1 mm deflection corresponds to a rise in temperature of $5° \times 10^{-6}$ and $7° \times 10^{-6}$, respectively. In other words, the instruments of the latter group have the same sensitiveness, and any increase is to be attained by lengthening the scale distance. The bolometer current of 0.04 ampere is about the maximum limit for accuracy. The sensitiveness of the writers' instruments could have been further increased by lengthening the scales distance to 2 m, when the temperature sensitiveness would have been $3°.5 \times 10^{-6}$, and by doubling the galvanometer period, when the sensitiveness would have been $1°.7 \times 10^{-6}$ against Paschen's $1° \times 10^{-6}$. Such a computation is of course somewhat illusory because of a difference in the galvanometer damping, and in the *radiation sensitivity* which is higher in a vacuum. On actual trial (using the 10-magnet system just quoted) for a full period of 20 seconds the sensitiveness of one of the writer's galvanometers was 7×10^{-11} ampere and on 30 seconds it was 3.7×10^{-11} ampere.

4. CONSTRUCTION OF A VACUUM BOLOMETER

A convenient vacuum chamber was made by combining the hemispherical mirror, *m*, with a small glass cup as shown in Fig. 10. The opening in the mirror is covered with a fluorite window, *f*, which is attached with cement. The glass window, *w*, admits viewing the inclosed bolometer strip for adjusting it in the spectrum. The exhaust tube, *t*, leads out along the axis to the rear of the bolometer case where it is joined (in series with a large, 4-liter, glass bottle to give it capacity and thus avoid variation in gas pressure) to a Geryk oil pump. The slate support of the bolometer strips, *b'*, *b'* (see Figs. 12 and 13 of the previous paper), is placed within this glass chamber, and the battery, shunt, and galvanometer wires, properly insulated, are inserted through the short tubes, *l*, and soldered directly to the terminals of the bolometer strips. All these joints are closed with a cement made of rosin and pure rubber which has a low vapor pressure. The exposed bolometer strip is brought in the focus of the hemispherical mirror by removing the microscope, E (Fig. 12 of previous paper), and reflecting sunlight along the axis of the bolometer from the rear. For this purpose the heavy battery current wires, which are the support of the bolometer holder, are of the proper length and flexibility to admit of such an adjustment. Two of the three sets of lead wires are illustrated in position in Fig. 10. The bolometer strips are 10 by 0.6 mm and have a computed thickness of 0.0003 mm and resistances of 5.604 ohms (exposed strip) and 5.664 ohms, respectively. The resistance of the complete bolometer is about 8.9 ohms (depending, of course, upon the battery current and the vacuum) with a temperature coefficient of 0.0230 ohms per degree. The resistance of the galvanometer is 5.09 ohms at 20° C, with a temperature coefficient of 0.0194 ohms per degree.

The rear side of each bolometer strip is left bright, and the front side is painted with a mixture of equal parts of lampblack and of platinum black, which is made into a smooth, thick, paste with turpentine, or with a dilute alcoholic solution of shellac. This is applied with a brush made of a thin strand of a fine silk thread. By starting at one support and by making one uniform stroke along the bolometer strip, and not stopping until after arriving at

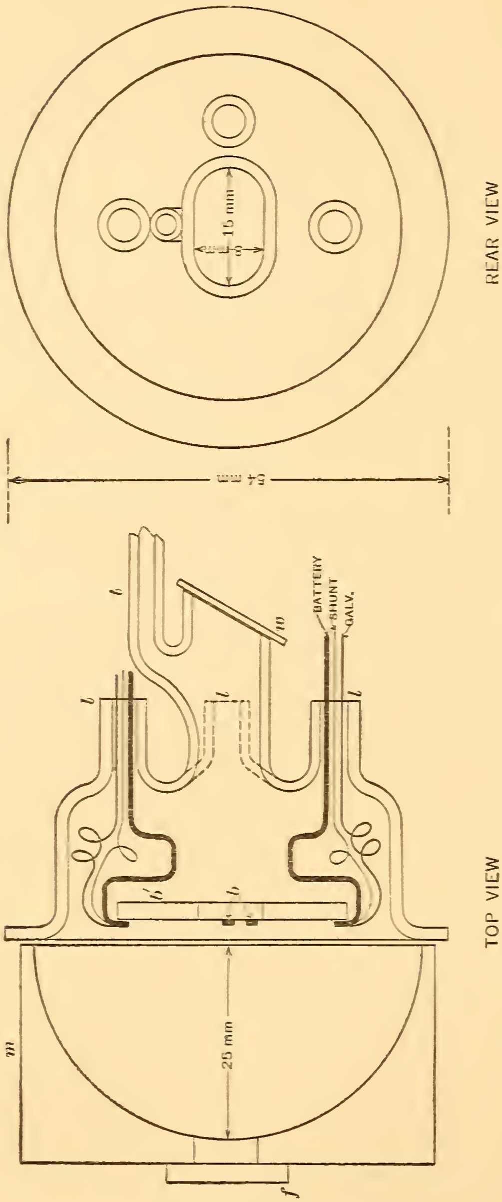


Fig. 10

the other end, there is no danger of tearing the strip. After this, the bolometer is blackened a little more by smoking over a candle flame. Chemically precipitated platinum black should be used instead of the powdered electrolytic material because it is blacker. However, a layer of platinum black, if successfully deposited electrolytically upon a bolometer strip, is the best of all.

The degree of evacuation is measured by means of the length of the cathode dark space in a small vacuum tube having disk electrodes of aluminum. There is practically no leakage when the stopcocks are in good condition and the vapor pressure from the cement is a fairly constant value, so that a cathode dark space of 2 mm (white CO_2 glow of hydrocarbon vapors) is easily maintained for weeks. The radiation sensitivity is lower for hydrocarbon vapors than for nitrogen or hydrogen, so that in practice air is admitted and the hydrocarbon vapors are pumped out. For example, starting with the bolometer after it has stood for some days at 0.2 mm pressure, when the hydrocarbon vapors predominated, the radiation sensitivity was doubled by admitting air and exhausting to the same pressure.

In practice, the sensitivity is varied by introducing resistance in series with the galvanometer. It is therefore necessary to determine the resistance of the bolometer with considerable accuracy, for different gas pressures, and for different values of battery current. As illustrated in Fig. 11, the resistance of the bolometer is practically constant for gas pressures as low as 0.2 mm. This degree of evacuation is sufficient to eliminate the effects of air currents, but the radiation sensitivity is not increased to a marked extent until a much lower vacuum is attained. This is illustrated in the upper part of Fig. 11, from Buchwald,[35] which shows the increase in sensitivity (the ordinates, which are the galvanometer deflections arising from exposing the bolometer to a constant source of radiation) with decrease in gas pressure; and also with increase in current. In this experiment the bolometer strip was 0.2 mm wide. In Fig. 9 using a bolometer strip 0.15 mm wide, the radiation sensitivity increased at a more rapid rate with decrease in gas pressure.

[35] Buchwald: Ann. der Phys. (4), 33 p. 928; 1910.

In the present bolometer the radiation sensitivity was doubled by reducing the gas pressure from 760 mm to 0.1 mm (6 mm cathode dark space). In hydrogen at 0.1 mm the bolometer was 2.5 as sensitive as in air at 760 mm pressure. With a Geryk oil pump a vacuum of 0.015 to 0.02 mm can be produced, when the radiation sensitivity is much higher. The sensitivity of this bolometer in air with the fluorite window in place was tested with a standard sperm candle placed at a distance of 2 m (an ordinary paraffin candle gives 10 to 12 per cent higher values). The

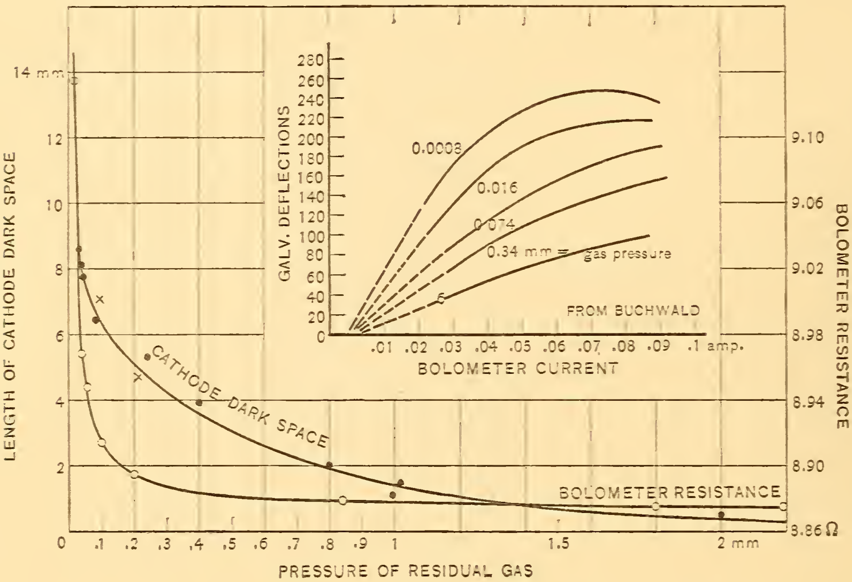


Fig. 11

fluorite window, which was flawless and 3 mm in thickness, transmitted about 93 per cent of the radiation from a sperm candle. The battery current was 0.03 ampere. Using a galvanometer period of 10 seconds and a sensitivity of 1.4×10^{-10} ampere, the mean value of the deflection was 30.1 cm, or 120 cm (129 to 130 cm when corrected for losses in the fluorite window) with a candle at a distance of 1 m, so that as ordinarily used, when evacuated to 0.1 mm pressure, the equivalent deflection would be at least 280 to 300 cm. Under these conditions an accuracy of 1 part in 200

to 400 is easily attained. In measuring weak radiation, the sensitiveness could be increased to at least 650 to 700 cm deflection by increasing the scale distance to 1.5 m, the galvanometer period to 12 seconds, and the battery current to 0.04 ampere, but keeping the pressure at 0.1 mm. By using the scale at 1.5 m, using a complete period of 12 seconds and a battery current of 0.03 ampere, but evacuating the bolometer to 0.01 mm or less, the radiation sensitivity would be increased two to three fold (600 to 900 cm). In qualitative work it is of course possible to use a higher sensitivity by using a large battery current, but in this bolometer the galvanometer deflection becomes unsteady when the battery current is higher than 0.04 ampere.

5. ELECTRIC BATTERIES FOR BOLOMETERS.

The general complaint against the bolometer is its "drift" caused by a gradual drop in the battery voltage or variation in bridge current.

While the bolometer is usually spoken of as being "simply a Wheatstone bridge," it is sometimes forgotten that, from the very nature of the construction of the bolometer, difficulties must be expected in operating it. A Wheatstone bridge is constructed of wires having a negligible temperature coefficient. In a bolometer two branches of the bridge are purposely constructed of metals having a high temperature coefficient of resistance. These two branches are made as symmetrical as possible in order that, when not exposed to radiation, they will be equally affected by temperature variations. But it is impossible to cut bolometer strips of the same width and mount them so that they will have the same resistance and the same radiating surface (emissivity). Hence, if the battery current varies, the resistance of one branch of the bolometer will vary more than the other and the bridge becomes unbalanced. One of the best balanced and most sensitive bolometers (the vacuum bolometer, already described) ever mounted by the writer would change in resistance so much that for a variation of $\frac{1}{1\,000\,000}$ ampere, the bolometer would be unbalanced by 1 mm. Of course, in the actual work the fluctuations in the deflections are greater than 1 mm. Formerly the writer operated

his bolometer on a portable storage battery which for several days after charging would give a sufficiently constant voltage so that there was no drift. Occasionally the galvanometer needle would vibrate when on shaking the storage cell (supposed to liberate the gas bubbles) or on substituting a new cell, the difficulty would be overcome. From this the writer concluded that the fault was with the battery. During the past two years he has used a large plate (single cell) battery of 400 ampere hour capacity, situated in a basement room (at uniform temperature) and has had no difficulties whatever from this source. The only fluctuations that arise are caused on windy days by air currents in the galvanometer, and in humid weather by grounding through the bolometer circuit.

Hulett[36] has described a battery which is really an enlarged form of cadmium sulphate cell. The cell gives good results while it lasts, but appears (in spite of its constancy) never to have given the satisfaction in bolometric work that was supposed to obtain when it was first described. On the other hand, the cell of large capacity (400 ampere hours) can be operated on a small battery current (0.03 in the writer's work) without variation in voltage. In actual practice, on standing over night, the unbalancing of the bolometer never amounts to more than 1 or 2 cm; usually it amounts to only a few millimeters and this is probably owing chiefly to a change in temperature and in the vacuum.

6. RADIATION SENSITIVITY OF DIFFERENT PARTS OF A BOLOMETER STRIP

Johansen[37] using a bolometer strip 11 mm long, 0.54 mm wide and 0.001 mm thick, found the sensitivity of different parts of the same when exposed to a standard source of radiation. For this purpose he projected (crosswise) an image of a Nernst glower upon different parts of the bolometer and noted the galvanometer deflection. At the ends, Fig. 12, the deflection is practically zero owing to loss by heat conduction. The errors resulting therefrom will be negligible when comparing sources of radiation which do not differ greatly in intensity. When the sources differ greatly in intensity, as for example, different parts of a spectral energy curve, the error

[36] Hulett: Phys. Rev., 27, p. 33; 1908. [37] Johansen: Ann. d. Phys. (4), 33, p. 517; 1910.

may be avoided by reducing the incident energy from the intensest source by means of a sectored disk. In the writer's vacuum bolometer the thickness of the strips is only about one-third that used in the above experiment. The loss by conduction from the ends is, therefore, much smaller and the sensitivity curve is flatter than that given in Fig. 12. The loss by conduction from the ends is further reduced by having the incident radiation cover only about two-thirds of the bolometer strip.

V. SELECTIVE RADIOMETERS

The well-known fact that the resistance of selenium changes, when exposed to the light, has been applied to photometric measure-

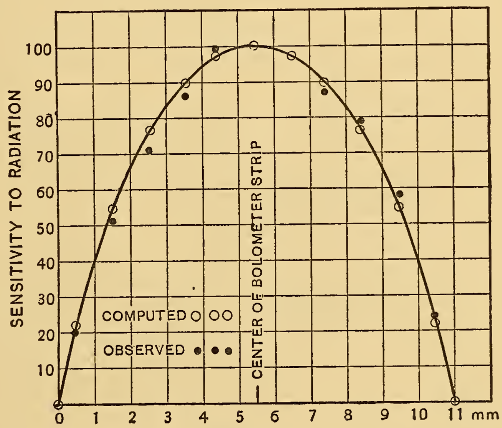


Fig. 12

ments. Pfund[38] has shown that the maximum sensitivity of the selenium cell is at about $\lambda = 0.7\ \mu$. According to Stebbins[39] some cells have two maxima, at $0.586\ \mu$ and $0.694\ \mu$, respectively. If an alloy could be produced which has its maximum sensitiveness (i. e., its resistance change greatest) for those wave lengths to which the eye is most sensitive, it might be possible to devise a method for measuring radiant efficiencies, without the use of an absorption

[38] Pfund: Phil. Mag. (6), 7, p. 26; 1904. From his latest work (Washington Meeting, Amer. Phys. Soc., Dec. 27, 1911, Phys. Rev., 34, p. 370, 1912), it appears that the position of maximum sensitivity varies with the intensity of the incident light so that the selenium cell does not appear to be a promising instrument in photometry or radiometry.

[39] Stebbins: Astrophys. Jour., 27, p. 138; 1908.

screen or a spectrometer, as now used for separating the visible from the infra-red.

In the ultra-violet the photo-electric effect has been applied by Küch and Retschinsky to measure the radiation from the mercury arc.[40] Little is known in regard to this class of radiometers. Since they are highly selective their application is limited, but if the proper combination could be found having a sensitivity curve similar to the eye it might be applicable in some special classes of photometric and radiometric work. If the transformation of radiant energy were as complete in the photo-electric effect as in a bolometer it would be a useful instrument, since it does not appear to be subject to such perturbations as is the bolometer. However, from the data at hand, especially that relating to the selenium cell, this type of radiometer does not appear to merit much of the attention that should be devoted to the further improvment of radiation instruments.

For determining the spectral energy distribution of weak and intermittent radiations, such as the flashes of light from the firefly, a species of spectro-photographic photometry has been employed [41] with considerable success. A "panchromatic" plate was used. The procedure consisted in photographing the spectrum of the light of the firefly and that of a standard lamp, after which the "densities" of the negatives were compared photometrically. The spectral energy distribution of the standard lamp was determined with a bolometer and from this the spectral energy curve of the light of the firefly was determined by multiplying the energy values of the standard glow lamp by the ratio of densities (firefly light ÷ glow lamp light) at each wave-length. The advantages of this method are, first, that all portions of the spectrum are recorded simultaneously, so that unsteadiness of the total light is permissible; and, second, that the plate is integrative, so that the obstacles imposed by low intensity may be overcome by long exposure.

---

[40] Küch and Retschinsky: Ann. der Phys. (4), **20**, p. 563; 1906.

[41] Ives and Coblentz: This bulletin, **6**, p. 321, 1909. Coblentz: Canadian Entomologist, p. 355, Oct., 1911; Carnegie Publication No. 164, 1912. Pierce: Phys. Rev., **30**, p. 663, 1910 (Fluorescence Spectra).

VI. A NEW FORM OF RADIOMETER

In the previous paper [1] a combination of the Boys radiomicrometer and the Nichols radiometer was described. The experiments showed that the combination is feasible,[42] but the time has never been opportune to continue the experiments to determine the proper dimensions of the suspension and the field strength of the magnets to attain the maximum radiation sensitivity. Bismuth was previously employed in the thermojunction; but it now appears that a short fine wire of constantan might prove more satisfactory, because it is not so diamagnetic.

Another type of radiometer (at least a type of radiation detector) suggests itself by taking advantage of the change in astaticism, caused by flexure of the vane joining a pair of suspended magnets. On a previous page it was shown that the change in astaticism of the galvanometer suspension was overcome by attaching the magnets with a cement which is not hydroscopic. This condition may be reversed, by joining two magnets by means of thin rectangular sheets of material having a high coefficient of expansion (e. g. ebonite) as shown in Fig. 13, A. The upper horizontal steel bar (dimensions 8 by 0.3 by 0.08 mm) is attached to a short glass rod which carries the mirror. The (vertical) vanes are painted black. Two vanes are used for symmetry, but only one is exposed to radiation. The bars are magnetized before mounting, and astatized after the suspension is completed just as is done with an ordinary galvanometer magnet system. In Fig. 13, B, is given a similar combination of fine steel wires joined together by means of light vanes, which takes the place of the vanes in an ordinary Nichols radiometer. This latter combination has not yet been tested to determine its utility. Some preliminary experiments were made on a pair of astatized magnets

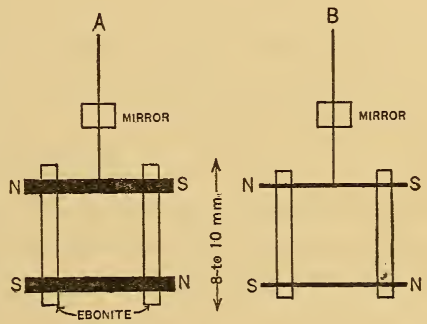


Fig. 13

[42] This Bulletin, 2, p. 479, 1906.

joined with radiation vanes (receivers) of blackened mica, and suspended in a glass tube by means of a quartz fiber. The earth's field controlled the equilibrium position of the system. In practice, of course, control magnets would be used as in galvanometers. When one vane was exposed to radiation there was an appreciable deflection. The experiment showed that the vane must be light (of low heat capacity) so that it will come to a thermal equilibrium in a short time. Furthermore the experiment showed that this method of measuring radiation, by changing the astaticism of a magnet system by flexure of the magnets, is feasible. Whether it will prove more sensitive than the more complicated radiometers herein described remains undetermined. The sensitiveness will depend, in part, upon the astaticism of the pair of magnets, upon the strength of the controlling field, and upon the length of the magnets. The investigation of these questions may require considerable time before it will be possible to report on the merits of this type of radiometer.

VII. SUMMARY

The present paper deals with four instruments for measuring radiant energy, viz, the radiomicrometer, the linear thermopile, the Nichols radiometer, and the bolometer with its axuiliary galvanometer.

As a result of this historical inquiry and by experiment it is shown that the radiomicrometer is capable of great improvement by reducing its weight, by lengthening its period, and by placing it in a vacuum. It was shown (in a previous paper) that on account of para- and dia-magnetism the sensitiveness of the short period radiomicrometer is limited to perhaps only one-half that of the best vacuum bolometers described. The instrument is free from magnetic disturbances which permits the use of a longer period; and by placing it in a vacuum of 0.1 mm or less pressure its sensitivity is comparable with that of a good bolometer. By properly shielding it from sudden changes in temperature and by using a long period the sensitivity of this instrument should excel all the other types.

It was shown that the Rubens thermopile is only about one-half as sensitive as a bolometer; but it can be greatly improved by

using thinner wires (0.06 to 0.08 mm diameter) and by using the instrument in a vacuum. The computed errors, due to the Peltier effect, are about 1 part in 300. The thermopile is not so well adapted as is the bolometer for instantaneous registration of radiant energy, and it does not admit so great a range in variation of sensitivity, but on account of its greater steadiness it commends itself for measuring very weak sources of radiation, e. g., the extreme ultra-violet and infra-red region of the spectrum.

A thermopile of bismuth-silver is described. It is easily constructed, and its sensitivity is from 2.5 to 3 times that of the iron-constantan pile. A surface thermopile is also described, the radiation sensitivity attained being six-sevenths the theoretical value.

By a direct comparison it was shown in a previous paper that the Nichols radiometer can be made just as sensitive as the bolometer, but its period will be much longer. It was found that the Nichols radiometer is not selective in its action, and hence that it can be used for measuring ultra-violet radiation. The main objection to the use of a Nichols radiometer is its long period, but since it is easily shielded from temperature changes and since it is not subject to magnetic perturbations, this long period is of minor importance so long as we are dealing with a constant source of radiation. In spectral energy work its usefulness is limited to the region in which the window is transparent. The fact that the Nichols radiometer deflections can not be obtained in absolute measure is a minor objection, since in but few cases thus far at least has it been necessary to thus obtain the deflections. The action of a Nichols radiometer is somewhat analogous to a photographic plate in that it will detect weak radiation, provided one can wait for it, and on account of its great steadiness is, of all the instruments considered, probably the best adapted to search for infra-red fluorescence.

A bolometer installation is so distributed that it is difficult to shield from temperature changes. In spite of its small heat capacity the bolometer has a "drift" due to a slow and unequal warming of the strips. Air currents which result from the hot bolometer strips also cause a variation in the deflections of the

auxiliary galvanometer. Nevertheless, despite these defects, it is the quickest acting of the four instruments considered and is the best adapted for registering the energy radiated from a rapidly changing source. For precision work it is necessary to keep the bolometer balanced to less than 1 cm deflection.

A vacuum bolometer is described, and data given showing that it is the quickest acting, the most relaible, and the most sensitive of all the instruments described having a short period.

A storage battery is described which gives a constant current, thus overcoming "drift."

The auxiliary galvanometer is the main source of weakness in measuring radiant energy, and in places subject to great magnetic perturbations a period greater than 5 seconds, single swing, is to be avoided. Hence, although a greater sensitiveness is possible, the working sensitivity of the various galvanometers studied is of the order of 2×10^{-10} ampere (per mm deflection on a scale at 1 m). Under these conditions the various bolometers used were (as a fair estimate of the recorded data) sensitive to a temperature difference of 4×10^{-5} degree to 5×10^{-6} degree per mm deflection on a scale at 1 meter. The galvanometer sensitivity was found to be closely proportional to the period. Methods are given to avoid changes astaticism, and to provide effective magnetic shielding.

A direct comparison was made in a previous paper of the relative accuracy of the thermopile and the air bolometer in measuring intense and weak sources of radiation, and the results show that there is little preference other than a personal one in these two instruments.

The manner of reducing the sensitiveness of these instruments is of importance in precision work. The use of the rotating sectored disk for reducing the intensity of the source is liable to introduce errors which must be taken into account. A new form of rotating sector is described. (See this Bulletin, 7, p. 249; 1911.)

It may be added that these tests were made in a building which is isolated from mechanical and magnetic disturbances, and hence under the most favorable conditions.

As a final remark it may be said that after four years of designing and testing various radiometers which were tried out on various researches, a bolometric outfit has been assembled which (while it

is not of the highest attainable sensitivity) excels all the other herein-described radiometers for speed and accuracy. It consists of (1) a vacuum bolometer which is free from drift and which admits of quickly and accurately adjusting the sensitivity throughout a wide range; (2) a galvanometer of high sensitivity and well shielded magnetically. The suspension is well damped on 2.5 seconds swing, has sufficient weight not to be affected by earth tremors, is free from the usual changes in astaicism, and has a wide range of proportionality of deflection with current; and (3) a satisfactory storage battery.

NOTE I. THE CALLENDAR RADIOBALANCE

Callendar[43] has recently described an ingenious device in the form of a thermoelectric balance for the absolute measurement of radiation. It consists essentially in exposing a thermojunction, in the form of a disk, to radiation and compensating or neutralizing the consequent rise in temperature by the Peltier (cooling) effect which is induced by sending an electric current through the thermocouple. Another thermojunction in contact with this disk indicates the degree of compensation. In actual practice, in the disk form of radiobalance there are two disks, J_1 and J_2 (Fig. 14, B), into which are soldered iron and constantan wires. One of the vertical wires, P_1 or P_2, is joined to an electric battery while the terminals of the horizontal wires (Fig. 14, B) are joined to a d'Arsonval galvanometer. When either disk, J_1 or J_2, is exposed to radiation the galvanometer gives a deflection which is then neutralized by sending an electric current through P_1 P_1, or P_2 P_2. With a given instrument the intensity of the radiation which can be directly compensated in this manner by the heat absorption due to the Peltier effect is limited by the Joule effect, I^2 R, in the wires forming the thermocouple. In practice it is necessary to know (1) the area, A, of the aperture admitting the radiation, (2) the coefficient, P $(=TdE/dt)$ of the Peltier effect in volts, (3) the current, I, through the couple, (4) the neutral current $I=P/R$, giving neither heating nor cooling, and (5) the absorption coefficient, *a*, of the blackened surface of the disk. When the radiation

[43] Callendar: Proc. Phys. Soc., London, 23, Pt. I, Dec. 15, 1910.

is exactly compensated by the current, the intensity of the radiation, H, in watts per square centimeter is

$$aAH = PI - I^2R = PI\ (1 - I/I_0).$$

Callendar says "the chief disadvantage of the radiobalance is that the increase of the Peltier effect per 1° C for the couples employed is very nearly 0.0001 volt in 0.0150 volt." It is therefore necessary to read the temperature of the thermometer to 0°.1 C. It is also necessary to find the value of the neutral current at various temperatures. After these two calibration curves have

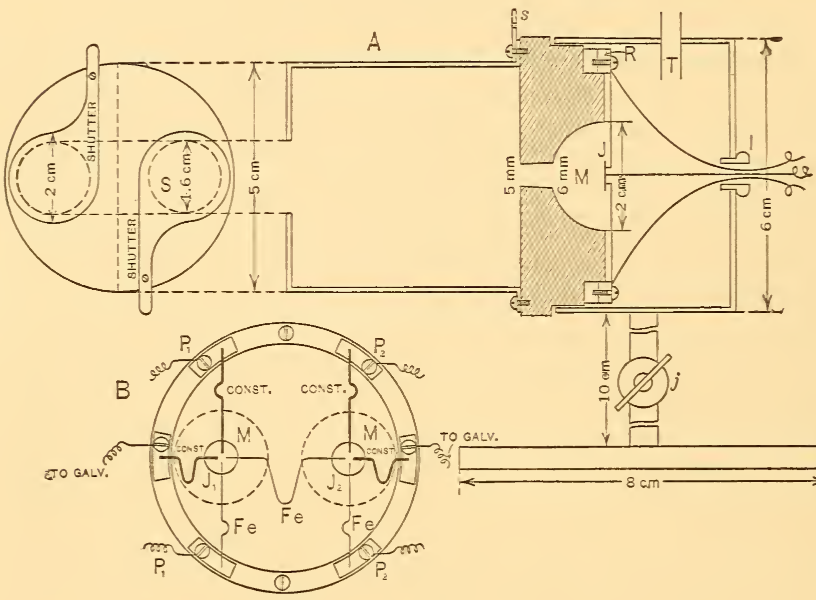


Fig. 14

been worked out it is a simple matter to expose either one of the disks to radiation, measure the compensating current with a milliammeter and read the thermometer, T, Fig. 14.

Callendar has also described a cup radiobalance in which the receiver is in the form of a cup about 4 mm diameter which is a more complete absorber than the disk. In this instrument the compensation is measured by a series of thermojunctions which are insulated from the cup.

The cup form of radiobalance appeared to be more difficult to construct than the disk. In the design shown in Fig. 14, the writer therefore placed each disk J_1 and J_2, in the focus of a small hemispherical mirror, M, 2 cm diameter, cut in a thick piece of brass and then highly polished. The disks were 5 mm diameter and about 0.25 mm thick. The openings in the mirrors for admitting the radiation were 5 mm diameter, but they were covered with a metal plate having apertures 2.3 mm diameter in order to be able to compensate the maximum radiation from the sun, which in this locality amounts to about 0.12 watts per sq cm per second. The lead wires, P_1 and P_2, of constantan (0.3 mm diameter) and iron (0.2 mm diameter) were soldered close together into the disks on a circle about 3 mm diameter and the ends were soldered to copper blocks, P_1 and P_2 which were mounted upon an insulating ring, R, of fiber. This ring can be readily attached over the hemispherical mirrors. The front of the instrument was covered with a tube to exclude stray light and to hold the shutters S.

The neutral current depends, of course, upon the resistance of the lead wires. Experiments were therefore made by increasing the number of iron and constantan wires attached to each disk (in Fig. 14, B, they are indicated by a single wire) from 4 to 8 and the neutral current was raised from 0.4 ampere to 1.2 amperes. The last design (having 9 iron and 6 constantan wires in each disk and requiring a neutral current of 1.084 ampere for J_1 and 1.120 for J_2 at 25° C) was given a thorough test against a Callendar sunshine recorder which had previously been calibrated against the Abbot primary standard pyrheliometer. In the first test (5:26:'11) the solar constant as measured with the radiobalance was 5 to 6 per cent *lower* than the value observed with the sunshine recorder. It is to be noted that, as in the original calibration of the sunshine recorder used in the present tests, the instrument was covered with a long tube, through which the sun's rays entered normally upon the receiving surface. The solar constant as measured with the two disks was in agreement to less than 1 per cent. It was therefore evident that the radiobalance was giving values which were about 5 per cent below the normal. In this test the ends of the thermojunction wires were about 2.2 mm apart on the disk.

They were then soldered close together in the center of the disks, J_1, J_2, but otherwise the instrument was unchanged. It was then found that the neutral current in J_1 had increased from 1.084 to 1.290 amperes and in J_2 from 1.120 to 1.364 amperes at 25° C. The solar radiation test was repeated (9:25:'11) with the surprising result that the radiobalance gave values, which, although in agreement to less than 1 per cent for the two disks, were 24 to 25 per cent *higher* than the value obtained by the sunshine recorder. In the third trial the thermojunction wires were separated about 1.8 mm and the solar radiation test was repeated on an unusually clear day (10:4:'11), when the air was free from dust. In this trial the radiobalance gave values which were 2.7 per cent higher than were obtained with the sunshine recorder. It is therefore evident that the supposed absolute values as determined with this radiobalance are erroneous and that in the last trial accident alone gave observed value so close to the true one. By trial one could of course place the junctions so that the errors would be negligible.

While it is disappointing to find that this instrument does not give directly the intensity of radiation in absolute value, it is possible to calibrate it against a known standard, just as was done with the sunshine recorder, when it should prove an excellent secondary standard pyrheliometer. The instrument just described is very sensitive, responding quickly to the passage of water vapor which is not visible to the eye. In fact, for low altitudes it follows the variation in atmospheric transmission with greater speed than is desirable. These comparisons are based on data obtained, when at intervals of two to four minutes, there was no fluctuation in the atmospheric transmission and when the thermometer reading was either stationary or was changing slowly. Furthermore, the maximum fluctuations in solar radiation, if they had been measured, could not cause the discrepancy herein recorded. The numerous details as to leakage, etc., were investigated and the only thing that will account for the results is the question of the location of the thermojunction in, and the temperature gradient of, the disk. That there is no exact temperature compensation is shown on testing the neutral current; for on throwing off the current the galvanometer gives a deflection

(owing, no doubt, to the heat generated in the wires which conducts to the junctions) which slowly returns to zero. The cooling effect is localized in the junction while the heating effect is along the whole length of the wires. This appears to be the weak point in the instrument. Whether the cup radiobalance gives more nearly the true value in absolute measure is undetermined. The measurements on a standard lamp, made by Callendar using a disk and a cup radiobalance, differ by about 12 per cent (disk = 0.0420 watt per cm^2; cup = 0.0373 watts per cm^2).

This great variation in absolute values is the common record of all the instruments yet described for the absolute measurement of radiation; and, as mentioned in the beginning of this paper, it is purposed to continue this study of various types of absolute instruments and report on the relative merits of the same at some future time.

APPENDIX I.

THE AUXILIARY GALVANOMETER

The illustration of the galvanometer previously described [44] has been corrected and modified. It is drawn to scale in Fig. 15, and needs no further explanation than that given in the previous paper. In the most recent work a strip of chamois skin is placed around the coils, completely inclosing them, except a small space in front of the mirror which is inclosed with a small window of plate glass. This inclosure is more effective in preventing air currents in the small space between the coils. Because of the difficulty in preparing a straight glass rod, the mirror is now placed on the center of the rod between the two groups of magnets, as shown in Fig. 15. To secure complete damping on 2.5 seconds single swing, a short strip of bolometer platinum, 0.0007 mm thick is attached to the glass rod, just below the mirror. Platinum is used because it does not hold an electric charge and, because of its thinness, it weighs very little.

The needle system in present use consists of two groups of tungsten steel magnets from 1.2 to 1.6 mm in length, 0.2 mm in width and 0.1 mm in thickness. They are mounted so that each group of magnets has the form of an ellipse. The mirror is of thin microscope cover glass about 1.5×2 mm, platinized by cathode discharge [45] and attached to the suspension with soft wax.

To make the suspension, the individual magnets are mounted upon a glass plate by means of LePage's glue. A little shellac is placed on the glass rod, which is then laid upon the two groups of magnets. After the shellac has dried the system is removed from the glass plate by soaking in water. The groups of magnets are

[44] This Bulletin, 4, p. 391, 1909.

[45] For details in making cathode mirrors, see papers by Longden, Phys. Rev., 11, p. 40, 1900; Leithauser, Zs. Instk., 28, p. 113, 1908; this Bulletin, 7, p. 197, 1911.

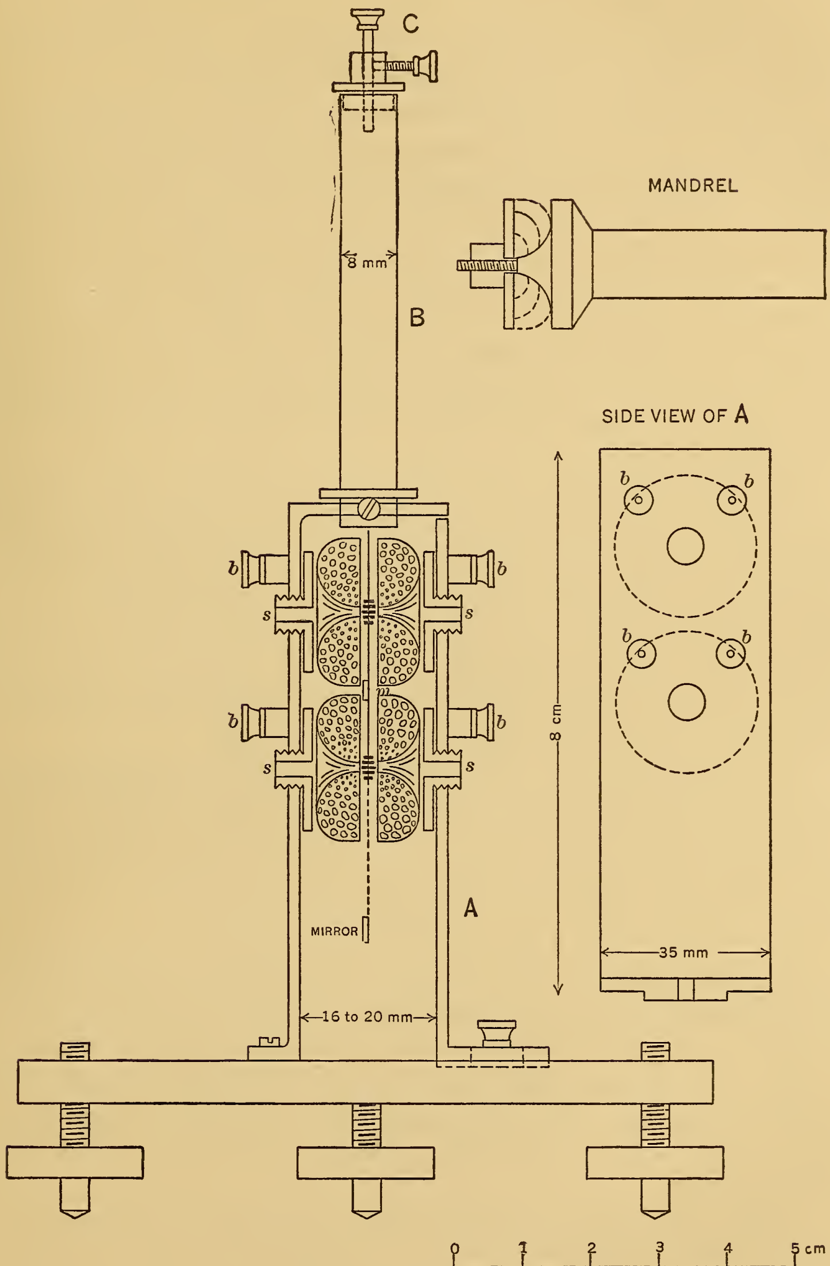

C
MANDREL
8 mm
B
SIDE VIEW OF A
b
b
b
b
s
s
b
b
b
b
s
s
m
8 cm
A
MIRROR
35 mm
16 to 20 mm
0 1 2 3 4 5 cm

Fig 15

then coated with asphaltum varnish to prevent moisture from being absorbed by the shellac. The magnets could of course be attached to the glass rod by using only the asphalt.

(*a*) **Sensitiveness of Galvanometer.**—In addition to the illustrations given in the previous paper, of the great variation that is possible in the galvanometer sensitivity by making slight changes in the suspension, the experience with a 12-magnet (6 in each group) system may be cited. By removing one magnet from each group, thus making the 10-magnet system shown in Fig. 15, the sensitivity was increased (by decreasing the weight) from 2.4×10^{-10} ampere to 1.4×10^{-10} ampere for the same period of 10 seconds and by adding the light damping vane of platinum (placed between the mirror and the lower group of magnets) this sensitivity remained unchanged.

The sensitivity of the galvanometer changes with the diurnal changes in the earth's field, so that when the humidity (which may affect the shellac on the magnets) is low, it is not an uncommon experience to find the galvanometer sensitivity to vary 10 per cent during the day, and have it return to practically its original value by the following morning. When the humidity is high, the shellac on the magnets warps the system, changing the astaticism sufficiently to mask the effect of the earth's field.

Wooden supports are also subject to warping with changes in humidity, which may shift the large iron shield relative to the galvanometer, thus changing the astaticism. This difficulty has now been overcome by having the galvanometer and its numerous iron shields rest upon one continuous base of marble.

The sensitiveness of the galvanometer (undamped) is approximately proportional to the square of the period. In the present tests the sensitiveness was found to be proportional to the period, owing to the air damping of the light magnet systems, as shown in Fig. 16, which gives the behavior of a 10-magnet system, with a platinum vane. It is just damped on 2.5 seconds single swing, the weight (about 8 mg) being sufficient to avoid the effect of earth tremors.

In the small coil galvanometer, the small mirror limits the use of the scale to a distance of 1.5 to 2 m, depending upon the planeness of the mirror. In the Du Bois and Rubens galvanometer the

mirror is large and the high sensitivity of this instrument is obtained by using the scale at a distance of 4.5 to 6 m. Present experience indicates that for prolonged routine work it is better to use mirrors about 2.5 by 3.5 mm area and attempt to gain in sensitivity by placing the scale at 2.5 to 3.5 m instead of having the scale at 1 to 1.5 m, which is the limit for smaller mirrors.

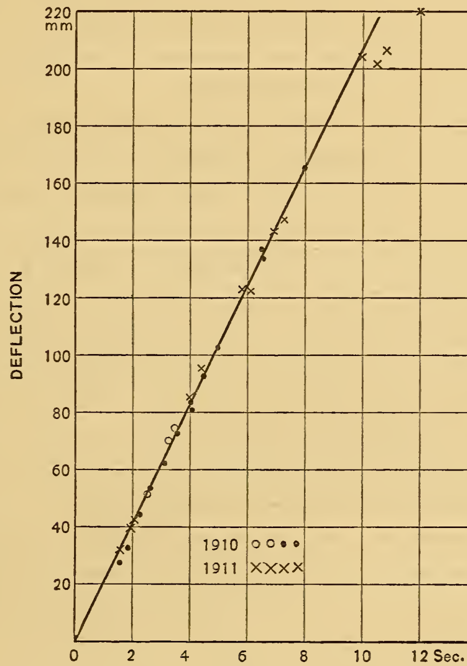


Fig 16

The present galvanometer suspension has not been remagnetized for about two years. During this time the sensitivity has decreased about 30 per cent.

(*b*) **Proportionality of Galvanometer Deflections.**—In the previous paper [46] experiments were described showing the relations between the currents through the galvanometer and the corresponding deflections. For a small coil (18 mm diameter, magnets 1 mm long) the deflections were proportional to the current up to

[46] This Bulletin, 4, p. 391, 1908.

about 7 cm. It was shown that by a judicious selection of longer galvanometer magnets, the proportionality of deflections with current may be made to hold true for large deflections (20 to 30 cm, which is practically the tangent law) with but slight loss in sensitiveness for a given period. This is well illustrated in Fig. 16, which gives the behavior of the 10-magnet system (5 in each group; magnets 1 to 1.6 mm long) provided with damping vanes and used in the present galvanometer having 20 ohm coils (5.09 ohms in parallel; coils 32 mm diameter). Here the proportionality holds to 18 or 20 cm deflection.

(*c*) **Magnet Shielding.**—For shielding a galvanometer magnetically, commercial soft iron pipe about 25 cm in length, and of various diameters, known as "black nipples," may be easily obtained. These shields usually become permanent magnets in handling, and there is great difficulty in lengthening the period of the galvanometer needle. It is therefore a matter of trial in placing the control magnets in such a position that they weaken the combined fields of the shields, and lengthen the period of the galvanometer. In fact, it was found easier to place a short magnet (steel file) under the galvanometer base so that it controls the suspended system and brings the mirror into view of the observing telescope, and then to weaken its field than to overcome the complex field (which, of course, remains but is not dominant) of the shields by means of the control magnets. A sheet of glass rests securely upon the iron shields upon which is placed a magnet (a large iron file) of suitable strength. To weaken the field of the short control magnet, which is placed near or under the galvanometer, this large magnet is rotated about a vertical axis until the galvanometer needle, which is following this rotation, passes through a neutral point, and rotates in the opposite direction. At this point the galvanometer needle will take a long period, provided the control magnets are not too strong.

For magnetically shielding the small coil galvanometer (coils 32 mm diameter) used in the present work, five sections of annealed soft steel pipe, about 30 cm long, inside diameter 7, 10, 15, 22, and 32 cm, respectively, and 4 to 6 mm thick are used. Within these cylinders of soft steel, and resting on the base of this galvanometer,

Fig. 15, is a laminated cylinder, about 20 cm high, of the best quality of transformer iron, made by rolling up and riveting 8 turns of iron 0.4 mm in thickness.

The mirror is viewed through slits 1 cm high cut into the shields. Although slits (borings, flaws, etc.) are considered detrimental [47] it appeared to make no appreciable difference in the shielding to use the slits and mirror far below the coils, or to have the slits at the center as now used in viewing the mirror between the coils, as shown in Fig. 15.

An inner shield was made [48] from Swedish iron which had a circular hole, bored vertically to admit the suspended system and the coils, which were mounted in paraffin. This inner magnetic shield was found to be superior to the others just described, since it is easier to anneal and does not become a permanent magnet in handling. The shield with the glass windows serves as a further protection against air currents. It is used with the 20-ohm coils (mentioned in the previous paper) which are 18 mm diameter.

Another inner magnetic shield is shown in Fig. 17, which gives a front and side view. It was made of two bars of Swedish iron, about 2.5 by 5 by 9 cm. The coils are imbedded in the iron as shown in the dotted lines in Fig. 17, by means of soft wax, the lead wires are brought out through glass tubes, t, and secured by brass screws, s, which are insulated in fiber. This is about the simplest mounting and shield that one can make. It is practically air tight, and its massiveness does not allow the coils and the inclosed air to follow sudden temperature variations. The whole should be given a thorough coating of shellac to prevent minute scales of oxide, which are formed on annealing, from becoming attached to the galvanometer needles. The following is an experience of this kind. The 32 mm coils and suspension, Fig. 15, were mounted in this shield. It was found that, starting with a certain period, e. g. four seconds, and the suspension in the zero position, when the suspension was deflected through a certain angle, the period changed and the deflection went off the scale. The exact cause of this could not be learned, but it appeared to

---

[47] Nichols and Williams: Phys. Rev., 27, p. 250; 1908.

[48] This bulletin, 4, p. 391; 1908.

be owing to a lack of symmetry of the distribution of the iron in this shield, which makes it less desirable than the preceding form. A somewhat similar experience was encountered with the (fully shielded) galvanometer illustrated in Fig. 17. When deflected to the right the needle began to drift, indicating a change in astaticism and an increasing period. No effect was observed when the

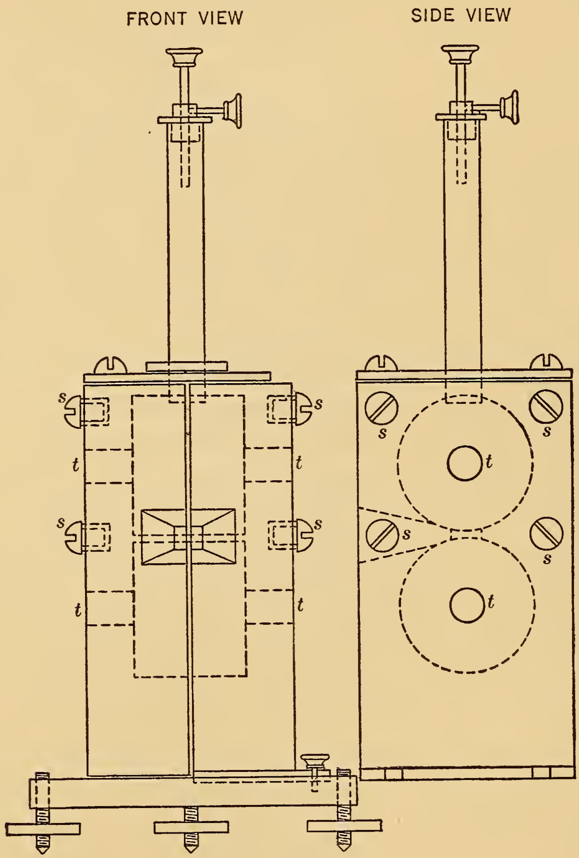


Fig. 17

suspension was deflected to the left. When examined under a microscope a small speck of iron oxide, about 0.05 by 0.1 mm was found pivoted on the end of one of the small magnets. On removing it the difficulty was remedied. Evidently as the magnet system rotated, thus changing the direction of the magnetic field

upon it, relative to that which obtained when in the zero position, the speck of iron oxide was acted upon in a different direction, and, being pivoted on the end, was free to turn, thus changing the astaticism of the suspended system.

It is customary to provide a symmetrical pair of control magnets (30 to 40 cm above the coils) placed upon a contrivance which permits an independent horizontal rotation and a vertical motion.[49] This is desirable in work extending over a long time, for the astaticism of the needle system is constantly changing, which requires a frequent adjustment of the control magnets in order to keep a fairly constant galvanometer period. As already mentioned, after painting the magnets with asphaltum (which is not hydroscopic) or mounting them therein, and after securely mounting the galvanometer and shields upon a suitable base, the writer has had no further difficulty with the change in astaticism. The galvanometer has retained a period of 2.5 to 3 seconds single swing for weeks without adjustment.

WASHINGTON, December 8, 1911.

---

[49] See Wiedemann's "Electricitat."